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Indian Standard

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APPLICATION GUIDE FOR ELECTRICAL RELAYS FOR ac SYSTEMS

PART I OVERCURRENT RELAYS FOR FEEDERS AND TRANSFORMERS

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BUREAU OF INDIAN STANDARDS
MANAK BHAVAN, 9 BAHADUR SHAH ZAFAR MARG
NEW DELHI 110002

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0. FOREWORD

0.1 This Indian Standard (Part I) was adopted by the Indian Standards Institution on 2 March 1967, after the draft finalized by the Relays Sectional Committee had been approved by the Electrotechnical Division Council.

0.2 Modern power systems are designed to provide uninterrupted electrical supply, yet the possibility of failure cannot be ruled out. The protective relays stand watch and in the event of a failure, short-circuits or abnormal operating conditions help de-energize the unhealthy section of the power system and restrain interference with the remainder of it, and thus limit damage to equipment and ensure safety of personnel. They are also used to indicate the type and location of failure so as to assess the effectiveness of the protective schemes.

0.3 In spite of the many refined protective schemes available today, the overcurrent protection has held its own because of its simplicity and economical cost. It is primarily used for the protection of feeders but has also been employed for the protective schemes of transmission lines, transformers, generators and other electrical apparatus. Subsequent to the publication of IS : 3231-1965*, it was felt that an application guide for overcurrent relays be prepared so that the system planning engineers may select and apply the overcurrent relays correctly from among the multitude of those available today.

0.4 The features which the protective relays should possess are:

a) reliability, that is, to ensure correct action even after long periods of inactivity and also after repeated operations under severe conditions;

b) selectivity, that is, to ensure that only the unhealthy part of the system is disconnected;

c) sensitivity, that is, detection of short circuit or abnormal operating conditions;

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*Specification for electrical relays for power system protection.

d) speed to prevent or minimize damage and risk of instability of rotating plant; and

e) stability, that is, the ability to operate only under those conditions that call for its operation and to remain either passive or biased against operation under all other conditions.

0.5 This application guide deals with only those relays which are covered by IS : 3231-1965*.

0.6 It is emphasized that this guide has been prepared to assist in selection rather than to specify the relay to be used. This guide deals only with the principles of application of overcurrent relays and does not deal with the selection of any particular protective scheme. The actual circuit conditions in all probability may be different from those discussed here. The examples, although drawn from actual field applications, should be regarded as mere illustration of one or the other point.

0.7 In the preparation of this guide considerable assistance has been derived from several published books and from manufacturers' trade literature. Assistance has also been rendered by State Electricity Boards in collecting actual examples.

0.8 This guide is one of the series of Indian Standard application guides for electrical relays for ac systems. The other guides in this series are:

IS : 3638-1966 Application guide for gas operated relays

IS : 3842 (Part II)-1966 Application guide for electrical relays for ac systems: Part II Overcurrent relays for generators and motors

IS : 3842 (Part III)-1966 Application guide for electrical relays for ac systems: Part III Phase unbalance relays including negative phase sequence relays

IS : 3842 (Part IV)-1966 Application guide for electrical relays for ac systems: Part IV Thermal relays

1. SCOPE

1.1 This guide deals with the application of overcurrent relays for ac systems, covered by IS : 3231-1965* for feeders and transformers. It covers both directional and non-directional overcurrent relays and their application for phase faults, earth faults, restricted earth faults and core-balance earth-fault protection. It also covers time-current characteristics and considerations for the setting and co-ordination of overcurrent (non-directional) relays.

*Specification for electrical relays for power system protection.

1.2 This guide does not cover:

a) the principles of system design and system protection,

b) direct acting overcurrent devices, and

c) static relays.

2. TERMINOLOGY

2.0 For the purpose of this guide the following definitions shall apply, in addition to those given in IS : 1885 (Part IX)-1966*.

2.1 Main Protection — Protection normally expected to take the initiative in case of a fault in the protected zone.

2.2 Back-Up Protection — Protection provided to act as a substitute for the main protection in the event of failure or inability of the latter to perform its intended function.

2.2.1 *Relay Back-Up* — An arrangement which provides an additional relay using the same or different principle of operation from that of the main relay.

NOTE — It is preferable to have separate current transformers, and if necessary, separate voltage transformers for relay back-up.

2.2.2 *Circuit-Breaker Back-Up* — An arrangement which provides isolation from source when the circuit-breaker nearest to fault fails to open or in case there is failure of the secondary current or voltage.

NOTE — It usually consists of a time-delay relay operated from the main protection and connected to trip all the incoming feeders.

2.2.3 *Remote Back-Up* — An arrangement at the next station in the direction towards the source which trips after a delayed time if the circuit-breaker in the faulty section is not tripped.

2.3 Residual Current — The algebraic sum of all the phase currents in a system.

2.4 Residual Voltage — The algebraic sum of all the phase-to-earth voltages in a system.

2.5 Knee Point Voltage — The sinusoidal voltage of rated frequency applied to the secondary terminals of a current transformer, all other windings being open-circuited, which when increased by 10 percent, causes the exciting current to increase by 50 percent.

2.6 Overreach — The tendency of a relay to operate for faults farther than its setting.

*Electrotechnical vocabulary: Part IX Electrical relays.

2.7 Percentage Transient Overreach — This is given by the following:

$$100\left(\frac{A-B}{A}\right)\text{ percent}$$

where

A = steady state rms value of operating current of the relay in amperes; and

B = steady state rms value of the current which, when fully offset will just operate the relay.

2.8 Resetting Ratio — The ratio expressed as a percentage of the resetting value to the operating value.

2.9 Resetting Time — The time which an operated relay takes in assuming the initial position as a result of a specified sudden change of the characteristic quantity, being measured from the instant at which the change occurs.

2.10 Overtravel (Overshoot) — The tendency of the moving parts of the relay to continue in the direction of their travel when the energizing quantity is removed.

NOTE 1 — The effect of overtravel is important where selectivity is obtained by time grading.

NOTE 2 — This is measured as the difference of time for which the relay is energized by a current corresponding to 20 times the plug setting to close its contacts and for which the same current should be applied in order to just prevent the contacts from closing.

2.11 Plug-Setting Bridge — A device providing a range of current settings for varying the relay operating current.

2.12 Pick-Up Errors — The error in the current value at which the disc starts to move and at which the contacts close, expressed as a percentage of the plug setting.

2.13 Time-Setting Multiplier — A means of adjusting the travel of the disc and thereby varying the time of operation of the relay for a given value of the fault current.

3. TYPES OF OVERCURRENT (NON-DIRECTIONAL) RELAYS

3.1 An overcurrent relay operates when the magnitude of the current in its circuit, supplied directly or from current transformers, exceeds a preset value. Most overcurrent relays have a number of current settings to make them suitable for a wide range of applications.

3.1.1 Mostly two overcurrent elements for phase faults, and one earth-fault element for earth-fault protection, shown as connected in Fig. 1, are used with due consideration to the current transformer polarity. These are sufficient on solidly-earthed system. Three phase-fault relays are

desirable on systems earthed through high impedance or unearthed. They are sometimes necessary on the delta side of delta-star transformers as the current in one phase may be twice that in the other two phases for a phase-to-phase fault on the star side. Earth-fault protection may also be provided by using core balance current transformers (*see also* **6.8.1**).

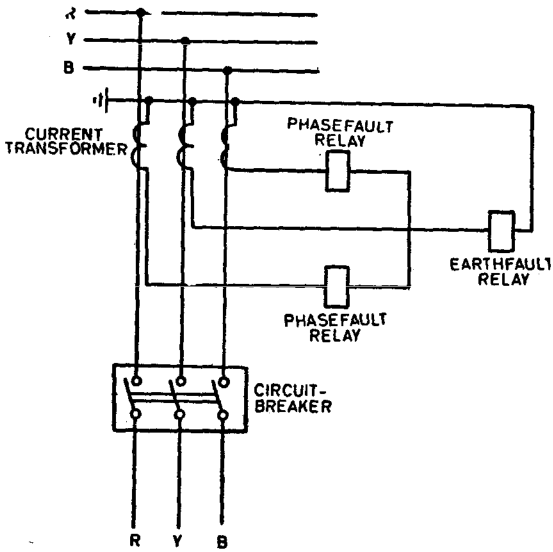


FIG. 1 APPLICATION OF TWO OVERCURRENT RELAYS WITH ONE EARTH-FAULT RELAY

3.1.2 Fault currents change in magnitude and phase while being transformed in delta-star transformers. An earth fault on the star side produces a circulating zero sequence current in the delta winding but no zero sequence current in the lines on the delta side of the transformer. An earth-fault relay on the delta side will not, therefore, respond to an earth fault on the star side of the transformers. For the purpose of gradation earth-fault relays the delta and the star sides thus become independent.

3.2 Overcurrent relays operate on one of the following principles:

a) Electromagnetic attraction
b) Electromagnetic induction, and
c) Permanent magnet moving coil/moving iron.

The details of each operating principle and the construction of relays may be obtained from text books or from manufacturers. The main

features of the relays, operating on the above mentioned principles are given in **3.2.1**, **3.2.2** and **3.2.3**.

The power required to operate an overcurrent relay and the impedance of the relay coil together with the impedance of the leads and current transformers should be known to determine the capacity and accuracy of current transformers. Relay impedance or burden is also given in the manufacturers' publications.

3.2.1 *Electromagnetic Attraction Type Relay* — The electromagnetic attraction type relays operate by a hinged magnetic armature attracted to the poles of an electromagnet or by a magnetic plunger drawn into a solenoid. These may be actuated by both dc and ac currents. Such relays are mostly instantaneous and are used where fast tripping on high magnitude of currents is required. Time delay, however, may be obtained by delaying mechanisms.

3.2.2 *Electromagnetic Induction Type Relays* — The electromagnetic induction type relays are essentially induction motors. Torque is developed in a rotor by the interaction of induced currents and fluxes to drive the rotor and thereby close or open the relay contacts. The induction relays operate on ac current only and are not affected by the dc component of a symmetrical short-circuit current. The induction type relays have a high resetting ratio and resetting value is normally higher than 90 percent of plug setting value.

3.2.3 *Permanent-Magnet Moving Coil/Moving Iron Relay* — The permanent moving coil type relays for ac application are provided with rectifier bridge and are essentially constituted by a magneto-electric measuring element which is associated with a system designed to obtain the restraining torque and consist of a delicate moving coil element. The operating time of this type of relay is normally below 100 ms depending on the following three variables:

a) magnitude of overcurrent,

b) gap between the fixed and moving contacts existing at the moment of fault appearance, and

c) damping.

Generally these relays have a low burden and wide range of adjustment.

3.3 Selectivity with overcurrent relays may be achieved by one of the following methods:

a) Grading the magnitude of the fault current;

b) Grading the time of operation;

c) Combination of (a) and (b) the most common method; and

d) Direction of the fault current.

4. TIME-CURRENT CHARACTERISTICS AND COMMON APPLICATIONS OF OVERCURRENT RELAYS

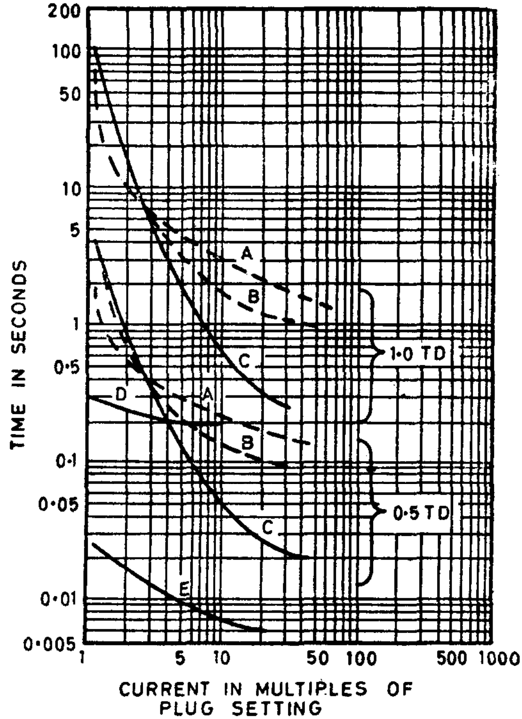
4.1 Overcurrent relays may have any of the following time-current characteristics:

a) Time delay,

b) Instantaneous, and

c) Combination of (a) and (b).

All these characteristics are shown in Fig. 2. Various time-current characteristics of overcurrent relays are discussed in **4.2** to **4.4**.



A = Inverse time

B = Very-inverse time

C = Extremely-inverse time

D = Definite time

E = Instantaneous

TD = Relay-time dial setting

FIG. 2 TIME-CURRENT CHARACTERISTICS OF VARIOUS OVERCURRENT RELAYS

4.2 Definite Time-Current Relays

4.2.1 These relays operate at a constant time predetermined by adjustment and are independent of current magnitude as long as it is sufficient to operate the relay. The time-current characteristic is shown by curve *D* in Fig. 2.

4.2.2 These relays are generally used for radial circuits or for those loop circuits which have a few sections in series and there is no difference between the fault current at the end of one section and the beginning of the next one. This relay is also used for back-up protection to differential and distance relays.

4.2.3 If there are several sections in series, say more than three or four, the time of operation increases as the fault location moves closer towards the source of power and thus the heavier faults get cleared in longer times.

NOTE — The resetting current or time or both are important where highspeed reclosing is used or if the breaker is not supposed to trip. There is a possibility that an abnormal condition may cause the overcurrent relay to operate but a return to normal condition for a relay with a low resetting current or a high resetting time is not possible and an undesired operation may result.

4.2.4 This relay may also be advantageously used on systems where the fault current at a particular point varies widely due to the changes in source impedance, as there is relatively small change in time with the variation of fault current.

4.2.5 For earth-fault protection, if the fault current is severely limited by neutral impedances or by arc or earth resistances, which is often the case in industrial plant systems, the definite time overcurrent relay may be used to facilitate co-ordination between two successive sections. In such cases it is recommended to use relays with similar characteristics.

4.2.6 Selectivity is achieved by time grading as shown in Fig. 3.

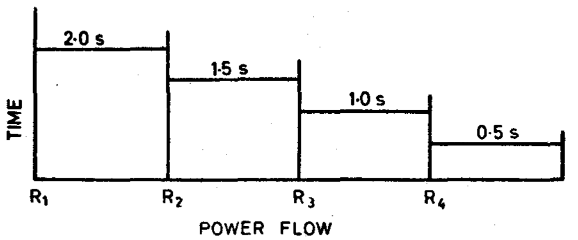


FIG. 3 DEFINITE TIME GRADING ON RADIAL CIRCUIT

4.3 Instantaneous Overcurrent Relays

4.3.1 Though classified as instantaneous, the time of operation of these relays may be up to 240 ms. It also varies with current magnitude at low currents as is shown in curve *F* in Fig. 2. The main difference between

various instantaneous relays is the resetting ratio which varies from 25 to 90 percent. The resetting ratio is important where the instantaneous .it is set near the full load current and initiates the tripping sequence .rough an auxiliary time-lag relay.

4.3.2 The instantaneous relays are very useful in reducing the time of ripping. However, since their selectivity is dependent solely on the nagnitude of the current, there must be a substantial difference (preferably a ratio of 3 : 1) in the short-circuit current between the two relay points to make them selective. This difference should also be greater than the fault current difference at the far end of the section for maximum and minimum generating conditions. In a transformer feeder the impedance of the transformer permits good selectivity of instantaneous overcurrent relays.

4.3.3 The instantaneous overcurrent relays are hardly used by themselves but when used, are invariably combined with time-delay overcurrent relays. By adding instantaneous overcurrent relays to inverse-time relays at each relay location point on transformer feeders or on long transmission lines the grading interval between inverse time relays can be shortened. With this arrangement the overall tripping time over a very large portion of the circuit can be reduced as explained in **6.3.2.1**.

4.3.4 Since the attracted-armature type relays are responsive to direct current as well, they are affected by the offset waves in the short-circuit current before the dc component dies out. The slower the decay of the dc component, the sooner the relay tends to operate. Thus the instantaneous overcurrent relays have a tendency to overreach and cause tripping for offset faults which are outside the zone of protection. The extent of the section that can be thus protected by these relays is dependent on the percent transient overreach of these relays. The overreach characteristic of certain instantaneous overcurrent relays is shown in Fig. 4. Instantaneous relays with low transient overreach characteristics are available.

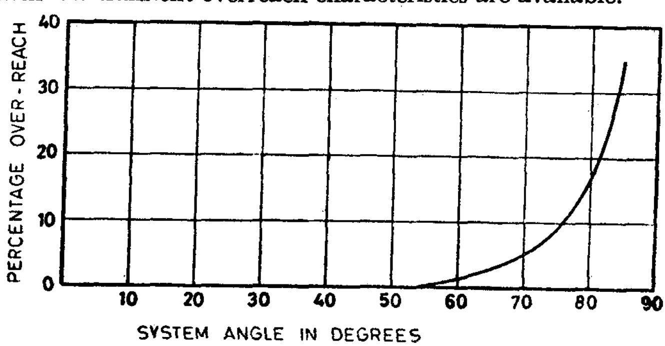


FIG. 4 OVERREACH CHARACTERISTIC OF A TYPICAL INSTANTANEOUS OVERCURRENT RELAY

4.3.5 If the generating capacity does not vary widely, the relays provide protection up to 80 percent of their protected zone, provided the source impedance is small in comparison to the circuit impedance.

4.4 Inverse Time-Current Characteristic

4.4.0 Most time-delay overcurrent relays are inverse-induction type. It means that the relay operating time decreases as the actuating current increases. Such relays are classified as 'inverse time', 'very-inverse time' and 'extremely-inverse time'.

4.4.1 *Inverse-Time Relays [Including Inverse Definite Minimum Time-Lag (IDMTL) Relays]*

4.4.1.1 Curve A in Fig. 2 shows the time of operation of an inverse-time relay whose operating time is proportionate to the energizing quantity (no simple mathematical expression for the characteristic of inverse-time relays is available). The most common type of these relays has got a definite minimum time and is generally known as IDMTL relay. These relays may or may not have instantaneous reset.

4.4.1.2 These relays are used on systems where system fault current at a particular point does not vary widely due to the change in source impedance. Its relatively flat time-current characteristic permits the relay to give reasonably fast operation over a wide range of short-circuit currents. These relays are generally used on systems where there is a wide difference between the fault currents at the end of one section and the beginning of next. The ratio of the fault current at the near end to the fault current at the far end is $\frac{Z_s}{Z_s+Z_l}$

where

Z_s = impedance between the relay and the power source, and

Z_l = impedance of the protected zone.

4.4.1.3 The above conditions are generally met in distribution net works and industrial plant systems.

4.4.1.4 The application of these relays on impedance earthed systems and in interconnected systems where the generating capacity varies between wide ranges, should be carefully studied. Such relays may also be used as back-up for differential and distance relays.

4.4.1.5 IDMTL overcurrent relay may be used for earth-fault protection if the fault current is limited by neutral impedances, by arc, or earth resistances which is often the case in industrial plant systems. To facilitate co-ordination between two successive sections, relays with similar characteristics should be used by grading the time or current setting or both.

4.4.1.6 Circuit breakers fitted with undervoltage release coils are protected by an IDMTL relay fitted with voltage operated relay as shown

in Fig. 5. The setting of voltage operated relay should be less than the resetting values of undervoltage release coil.

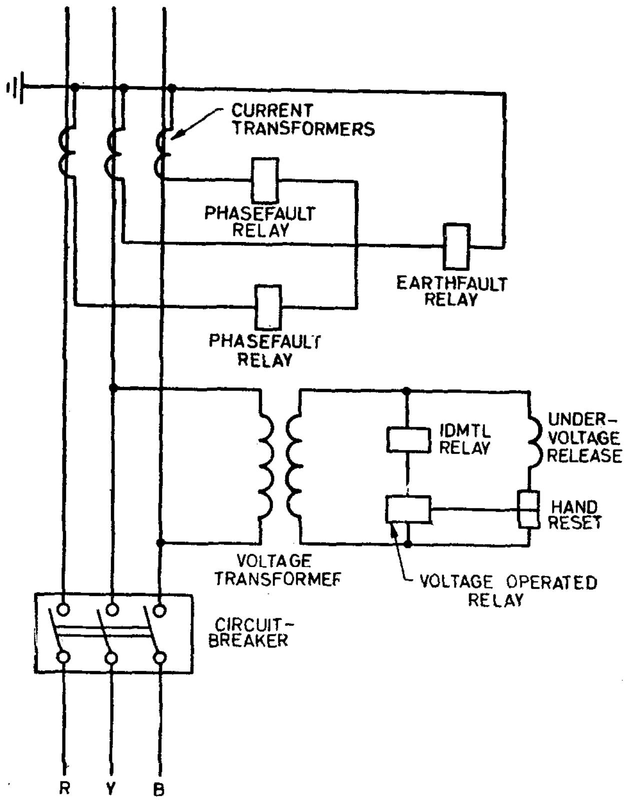


FIG. 5 PROTECTION OF CIRCUIT-BREAKER FITTED WITH AN UNDERVOLTAGE RELEASE COIL BY AN IDMTL RELAY

4.4.1.7 Theoretically the time of operation should be proportionate to the time multiplier setting but on account of the inertia of the rotor this is not possible at low current values. Since standard relays are built on a production line basis, certain tolerances in operating times are allowed. Figure 6 illustrates the permissible errors in accordance with IS : 3231-1965*.

*Specification for electrical relays for power system protection.

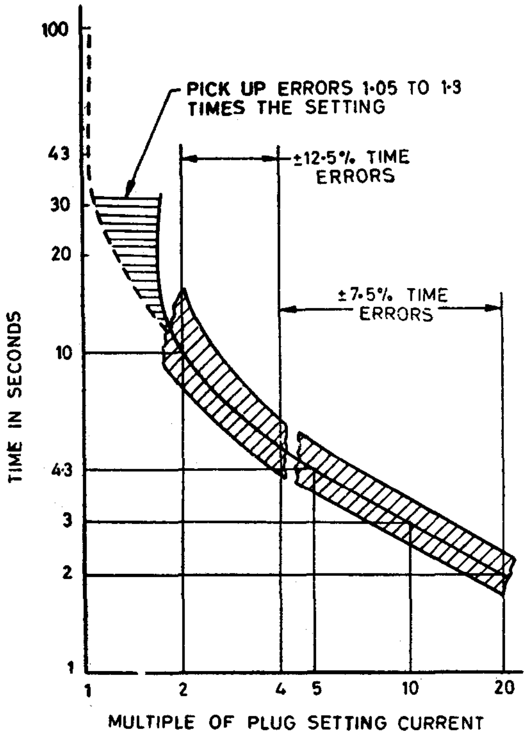


*FIG. 6 PERMISSIBLE ERROR AT TIME MULTIPLIER SETTING FOR PROTECTIVE RELAYS

4.4.2 *Very-Inverse-Time Relays*

4.4.2.1 The time-current characteristic of such relay is shown by curve *B* in Fig. 2 and is expressed by $I_t = K$. These relays are suitable for the following applications:

a) Feeders supplied from large generating systems where the short-circuit current magnitude is practically constant;

b) Long sub-transmission lines where there is a substantial reduction in fault current as the distance from the power source increases;

c) Loop systems where it is necessary to have approximately the same interval between operating times for faults at the near end and far end of the protected section; and

d) Where fast operation is required over a restricted current range.

4.4.2.2 Figure 7 gives a comparison of the very-inverse and inverse time-current characteristics.

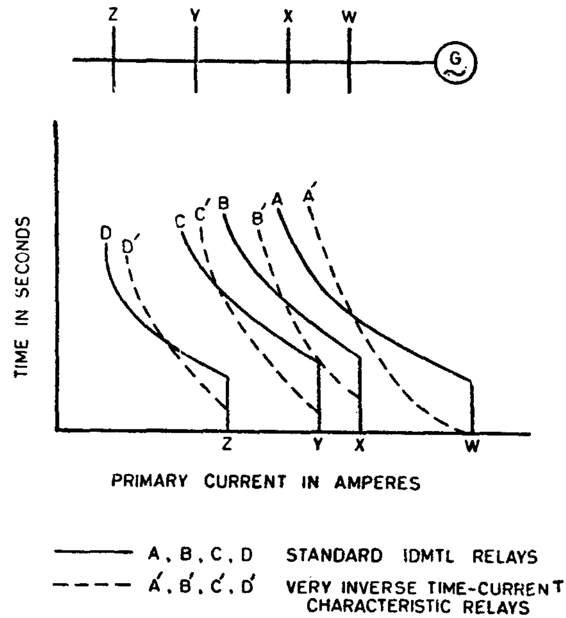


FIG. 7 COMPARISON OF VERY-INVERSE AND INVERSE TIME-CURRENT CHARACTERISTICS

4.4.3 *Extremely-Inverse Time Relays*

4.4.3.1 Curve *C* of Fig. 2 shows the time-current characteristic of extremely-inverse relays. The characteristic of this relay can be represented by $I^2t=K$. Since only a small difference in current is necessary to obtain adequate selectivity, this relay is very useful for distribution and industrial feeders where it is necessary that the relay should ride through the high initial load current when a feeder is energized after an outage and yet provide fast operation on short-circuit faults. Because its characteristic is the same as the heating characteristic of most of the electrical apparatus, it is also useful for protection against over heating. Typical applications are earthing transformers, power transformers, cables and railway trolley wires.

4.4.3.2 It also provides accurate discrimination with fuses and auto-reclosers which can seldom be made selective with standard IDMTL relays.

Care should also be taken in applying these relays on systems where standard IDMTL relays are used and co-ordination between the two types shall be checked.

4.4.4 *Special Inverse-Time Characteristics* — The time-current characteristic of enclosed fuses approximates to $I^{2.5}t=K$ and even the extremely-inverse relays cannot be considered to provide 100 percent discrimination with them. Only static relays can achieve still more inverse characteristics than the extremely-inverse relays. It is possible to obtain the characteristic $I^nt=K$, for $n>2$ at higher currents by altering the circuit parameters of the static relays. For mercury arc rectifiers which have a time-current characteristic of $I^8t=K$, the static relays are admirably suitable.

5. DATA REQUIRED FOR RELAY SETTINGS

5.1 Basic Data — The basic data required before determining the settings of the relays are given below·

a) A single-line diagram of the system which should give the ratings and impedances of rotating plants, transformers, feeders, etc. It is desirable that any likely additions in the near future are also included. The details of instrument transformers and the protective relays and other devices should also be shown.

b) Maximum and minimum values of short-circuit currents at all the relay points. Short-circuit current contributed by the users' own power generators and other rotating plants should also be considered.

c) Characteristic curves of current transformers.

d) Characteristic curves of the relays, circuit breaker series trip coils, and the fuses which have to be co-ordinated.

5.2 Fault Currents for the Operation of Overcurrent Relays — The type, settings and time of operation of the overcurrent relay depends upon the magnitude of the fault current.

5.2.1 *Hinged Armature Instantaneous Relays*

5.2.1.1 Since these relays can operate within the first half cycle of asymmetrical fault current, sub-transient reactance of the rotating plant should be used for calculating the fault current for the operation of these relays, if situated near the generating plant. In industrial distribution net work, the contribution of fault current by synchronous machines and local induction motors should also be included. The symmetrical fault current should be multiplied by 1·6 to obtain the magnitude of the asymmetrical fault current.

5.2.1.2 At locations remote from generating plant where the effect of transmission line, transformers or cable impedances are predominant the decrement effect is negligible. Therefore, in such cases only the transient

reactance of the rotating plant need be considered. This also applies to relays where time of operation is one cycle or more.

5.2.2 *Time-Delay Induction Relays* — These relays are too slow to be affected by the sub-transient reactance and their maximum operating current is the initial value of symmetrical fault current on the basis of transient reactance. However, where these relays are being used for back-up protection near the generating station which supplies most of the fault current, generator short-circuit decrement curves should be consulted for determining the pick-up of the relays particularly if the operating time of the relay is 1 second or more.

5.3 Setting of Relays — The current settings of relays should be high enough to carry normal overloads and yet low enough to operate the relay positively on the minimum short-circuit current. Normally there will be plenty of margin between the two values. Occasionally the difference may be small and discrimination between the two doubtful. In such cases, it is better to specify relays that do not operate on current magnitude alone, such as, voltage-controlled relays. For every relay, two settings, that is, current and time settings, are required.

6. SETTING AND CO-ORDINATION OF OVERCURRENT RELAYS FOR FEEDERS

6.1 General

6.1.1 Overcurrent relays may be used both for main as well as back-up protection. Modern practice is to use distance, carrier and pilot wire schemes for the main protection of high voltage feeders. Overcurrent relays provide the most economical and reliable back-up protection for phase and earth faults. Sometimes distance relays are used for the main protection against phase faults only. The overcurrent relays then are used for the main protection against earth faults. Two typical applications of the overcurrent relays for back-up protection are shown in Fig. 8 and 9. In Fig. 8 a standard IDMTL relay is used while in Fig. 9 overcurrent relay with definite time-lag characteristic is shown. Remote back-up relaying with overcurrent relays, however, is made ineffective sometimes on inter-connected power systems or where power is in-fed at a number of locations.

6.1.2 Faster back-up times can be achieved with a non-directional inverse-time overcurrent relay with an instantaneous unit as shown in Fig. 8. As the reach of the time-delay overcurrent relays (IDMTL and definite time) varies with generating conditions and in-feed, these may cover at times more than one line section. Therefore, these relays shall be given a time setting of at least one second, that is, corresponding to the third zone time setting of a distance relay. Referring to Fig. 9, a fault at *X* is normally cleared by the distance relay at *B* if the distance relay at *C* fails to operate. If the distance relay at *B* cannot operate because of a

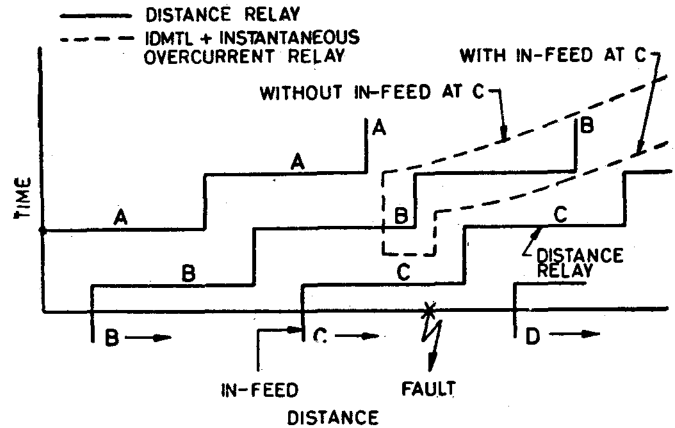


FIG. 8 LOCAL BACK-UP PROTECTION WITH INVERSE AND INSTANTANEOUS OVERCURRENT RELAYS

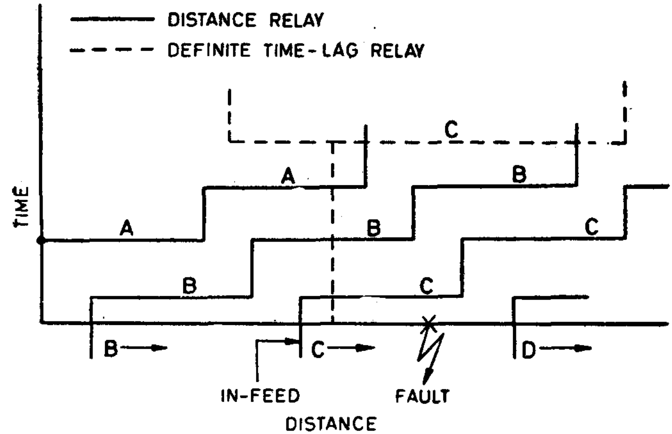


FIG. 9 LOCAL BACK-UP PROTECTION WITH DEFINITE TIME-LAG OVERCURRENT RELAYS

heavy in-feed at *C*, the time-delay overcurrent relay at *C* will operate and clear the fault. For a fault near the bus-bar *C*, if distance relay at *C* fails to operate, distance relay at *B* will operate earlier than the time-delay overcurrent relay at *C*. Therefore, back-up protection for line faults will be always available.

6.2 Settings for Definite Time-Lag Relays — On account of the factors mentioned in **4.2**, the earth-fault current on certain systems may be of very low value for which relays with 5 percent or less settings should be used. However, relays with such low settings are susceptible to maloperation due to unbalance in load currents or current transformer output and therefore while applying these relays manufacturers should be consulted. Where these relays are used as back-up protection for high voltage feeders reference may also be made to **6.1** (*see* Fig. 9).

6.3 Setting of Instantaneous Overcurrent Relays — Maximum use of instantaneous overcurrent relays along with the standard IDMTL relays is made on long transmission lines and on sub-transmission line transformer feeder circuits which provide sufficient impedance between two relay locations (*see* **7**). The relays protecting the feeders but located near the power source should be set for faster operating times than those protecting the generators. In industrial and distribution systems instantaneous relays cannot be made selective on ordinary lengths of cables because the circuit impedances are too low to provide the necessary current differential between two successive relays in series. It is preferable, therefore, to use the instantaneous relays on the branch feeders at the receiving end of the main feeder cables. This provides fast selective tripping of the branch circuits in trouble. Had the instantaneous relays been used on the main feeders, a fault on one of the branch feeders would have shut down all the branch circuits regardless of the fault location. However, on systems where instantaneous relays can be used the considerations mentioned in **6.3.1** and **6.3.2** govern the setting of relays.

6.3.1 *Phase-Fault Relays* — The following considerations govern the settings of the instantaneous overcurrent relays for phase faults:

a) The relays should operate for the maximum fault current well within the far end of the protected zone, and

b) The relay should be adjusted not to operate for a fault in the adjoining zone when the maximum fault current flows.

To meet the above two considerations, account should be taken of the overreach characteristic of the instantaneous overcurrent relay. Where accurate data is not available and the source to line impedance ratio is small it is recommended to set the relays to operate at 125 to 135 percent of the maximum symmetrical fault current at the far end, that is, the relay protects about 70 to 80 percent of the feeder or the protected zone. However, to allow accurately for the overreach, percent transient overreach curve for the relay, similar to the one shown in Fig. 4, should be obtained from the manufacturer.

NOTE — The maximum fault current is the 3-phase fault current for such relays. The line coverage for phase-to-phase faults will be slightly less.

6.3.1.1 An example of the setting of the above type of relay is given below:

Assume that the instantaneous overcurrent relay has an overreach of 20 percent for a fault whose steady state component of current is 16A. If the relay is not to operate for this fault, the relay setting must exceed:

$$\frac{100\,B}{100 - \text{percent transient overreach}} = \frac{100 \times 16}{100 - 20}$$
$$= 20\text{ A}$$

where

B = steady state component

Thus the setting of the instantaneous overcurrent relay should be above 20A. It may be added that nowadays instantaneous overcurrent relays with low overreach characteristic are available.

6.3.2 *Earth-Fault Relays* — The principles of setting for the earth-fault relays are the same as for phase-fault relays, except that the value of fault currents for setting a relay should be for a single line-to-earth fault. Generally a setting of more than 20 percent will give adequate protection and it is better not to adopt too low a setting (*see also* **6.2**).

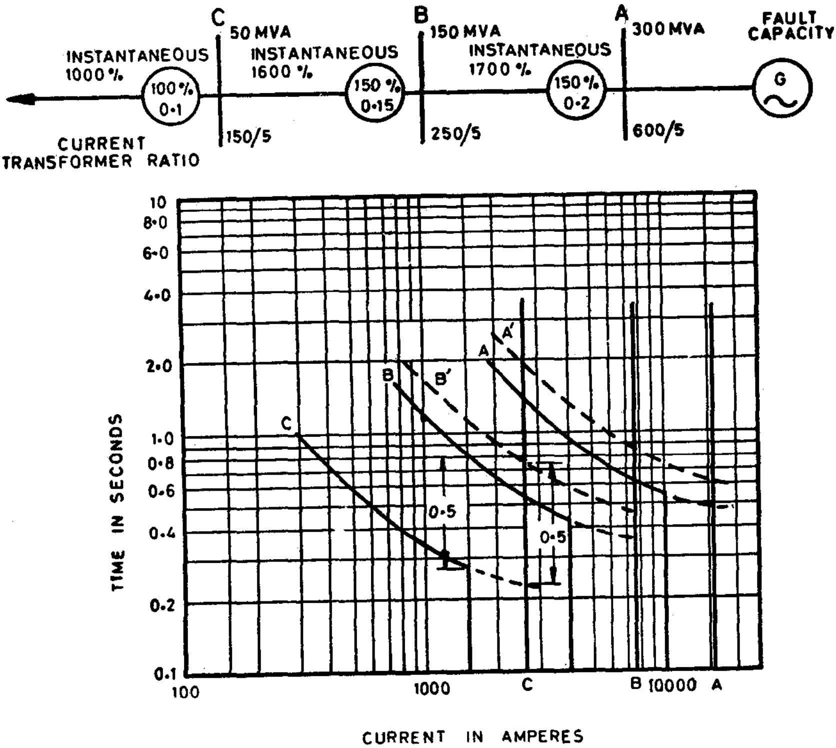
6.3.2.1 In Fig. 10 is given an example of the use of instantaneous overcurrent relays along with standard IDMTL overcurrent relays. It may be seen that with the use of high set instantaneous overcurrent relays, the IDMTL relays at *A*, *B*, and *C* need be selective only at the reach point of the instantaneous overcurrent unit. Thus in addition to obtaining high speed protection, for about 80 percent of the line, faster tripping times for the IDMTL relays are possible as an additional advantage.

6.4 Settings for IDMTL Relays

6.4.1 *Current Settings*

6.4.1.1 The reach of the relay should be up to the end of the adjoining section for the minimum fault current. Phase-to-phase fault current should be considered for phase-fault relays, and line to earth-fault current for earth-fault relays.

6.4.1.2 The settings for phase-fault element may be as high as 150 to 200 percent of full-load current. The relay shall not operate at a current equal to or less than the setting and the minimum operating current shall not exceed 130 percent of the setting. While choosing the setting, account should be taken of the minimum operating current of the relay. The earth-fault element is not affected by the 3-phase balanced current and may therefore be set at low values. Generally, the setting of these relays is between 20 to 80 percent of the current transformer rating. The effects of arc and earth resistance should also be considered. Earth resistance may range over such wide limits that the only practical thing to do is to measure the value for any given locality. As for the arc resistance, at least the resistance of the arc when it first occurs should be taken into account.



NOTE — *A* and *B* are IDMTL characteristic curves when instantaneous units are not used.

FIG. 10 APPLICATION OF IDMTL RELAYS WITH HIGH-SET INSTANTANEOUS OVERCURRENT UNITS

6.4.1.3 Earth-fault relays are liable to maloperation due to the following reasons:

a) Saturation of current transformers during phase fault,
b) Unbalanced currents from current transformers or the normal system load unbalance, and
c) Induction effects in a parallel unfaulted line for earth faults on the faulted line.

In most cases, the difficulties may be overcome by increasing current setting or the time delay. A low setting should be used with utmost care specially in solidly earthed systems which produce high earth-fault currents.

6.4.1.4 To take advantage of the inverse part of the characteristic, the highest possible current setting should be chosen.

6.4.1.5 Where the overload-withstand ability of relays is also a factor to be considered, the current through the relay should be limited to about 20 times the lowest current setting by adopting a higher current setting or a higher current transformer ratio.

6.4.2 *Time Settings*

6.4.2.1 The relay farthest from the supply source should be set for the lowest possible operating time.

6.4.2.2 Co-ordinating time intervals which are usually of the order of **0.4** to **0.5** seconds should be allowed between the time of operation of two adjacent relays. However, it will be necessary to calculate the co-ordinating time interval if a lower co-ordinating time interval is required.

6.4.2.3 *Example showing the calculations for the co-ordinating time between two adjacent relays*:

The difference between the operating time of the adjacent relays:

$$T_1 - T_2 = B_2 + O_1 + E + F$$

where

T_1 = the operating time of the relay at location 1,

T_2 = the operating time of the relay at location 2,

B_2 = the opening time of the breaker at location 2,

O_1 = overshoot of relay at location 1,

E = errors in the operating times of relays at location 1 and location 2 (made additive to allow for a bigger safety margin and are in accordance with IS : 3231-1965*), and

F = the safety factor.

Values for a typical relay are as below:

Breaker time	0·1 to 0·16 second
Overshoot	0·04 to 0·1 second
Relay errors at locations 1 and 2	0·2 to 0·3 second

NOTE — The relay errors can be more accurately calculated when the fault current and the time setting multiplier are known.

Factor of safety	0·06 to 0·1 second
Total time	0·4 to 0·66 second

6.4.2.4 Adjustment should be made for the maximum 3-phase symmetrical fault current for a fault located beyond the adjacent relaying point. This will ensure selectivity for lower fault currents.

6.4.3 The following example shows the calculations for the setting of a relay with IDMTL curve whose time-current characteristics are shown in Fig. 11.

*Specification for electrical relays for power system protection.

It is required that the relay operates in 2 seconds on a short-circuit current of 6 000 A. The current transformer ratio is 400/5 and the normal full-load current is 300 A. The relay current setting range is 50 to 200 percent in steps of 25 percent.

Let the current setting be at 125 percent, that is, about 66 percent above the normal full-load current:

Then secondary value of short-circuit current $= \frac{6\,000 \times 5}{400} = 75$ A; this corresponds to 12 times the plug setting of the relay (6·25 A).

From Fig. 11, at 12 times the plug setting, the time of operation of the relay is approximately 2·8 seconds if the time setting multiplier is 1. Therefore, the time setting multiplier should be adjusted to:

$$\frac{2}{2{\cdot}8} \simeq 0{\cdot}7$$

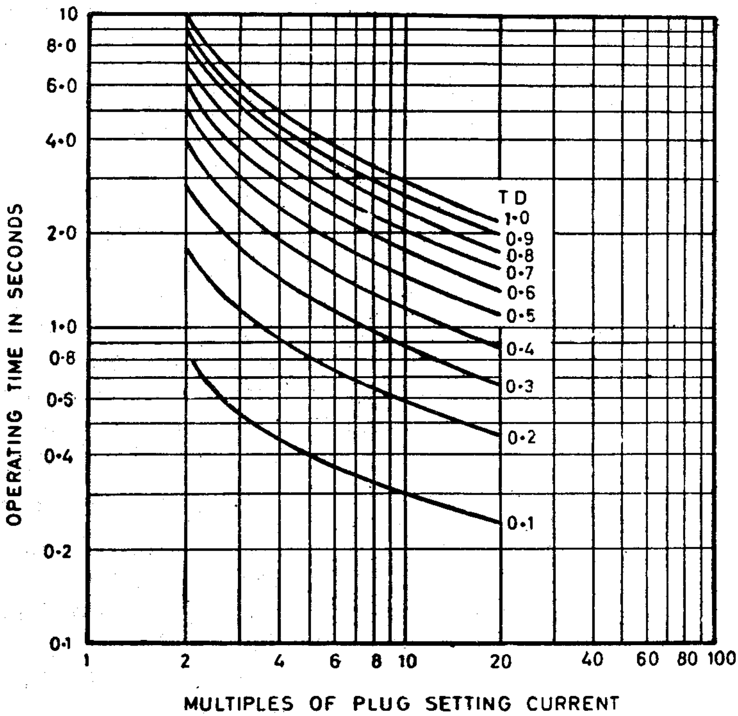


FIG. 11 TIME-CURRENT CHARACTERISTICS OF A STANDARD IDMTL RELAY

NOTE — As the operating current may be up to 1·3 times the plug setting, it is preferable to set the relay at 100 percent which would provide better protection against prolonged overloads. In this case the time setting multiplier would be 0·8 to get the operating time equal to 2 seconds.

6.4.3.1 *Setting and co-ordination of IDMTL relays — phase-fault relays —* Figure 12 shows a simple radial circuit being fed at end *A* only. At each station the fault level and the current transformer ratios are indicated.

For deciding the setting and co-ordination, the first step is to prepare a transparent template of the time-current characteristics of the relays used for the protection of the circuit. This is made by plotting the relay characteristic corresponding to the time setting multiplier of 1 on a log graph paper in such a way that the origin corresponds to 1 second along the *Y* axis and 100 percent plug setting along the *X* axis. A typical template curve is shown in Fig. 13. The curve is then transferred on to a transparent material.

To obtain the settings at the various substations in the radial circuit shown in Fig. 12 the setting of the relay farthest from the source is taken up first. The maximum 3-phase-fault current at this station is 50 MVA at 11 kV, that is, 2 620 A. This is 52 times the primary rating of the current transformer, well over its saturation value. In order to obtain the lowest possible time of operation at this location the plug setting of 100 percent and the time setting multiplier of 0·1 are selected. A log log graph is prepared with time in seconds along the *Y* axis and current in amps in the primary circuit at 11 kV along the *X* axis, as is shown in the lower half of Fig. 12.

The next step is to transfer the curve on the transparent template to this log log graph so that the origin of the template rests against 50 A and 0·1 second, that is, 100 percent plug setting and the time multiplier scale of 0·1.

The relay setting at location *D*, that is, next to substation *E* should give a discrimination of 0·5 second (or whichever co-ordination time interval is decided). The template is moved on the log log graph so that the time of operation of the relay at *D* must not approach that of the relay at *E* by less than 0·5 second up to the maximum value of fault current that can flow at station *E*. It will be seen that the settings at *D* come out to 150 percent and 0·3 second. The procedure for setting the relays at stations *C*, *B* and *A* is the same. The current and time settings and the characteristic graphs at these stations are shown in Fig. 12.

A further advantage of this method is that the circuit-breaker operating time, the overshoot and the relay error may be plotted to see that the safety factor is reasonable. In Fig. 12 this is shown for stations *B* and *C*.

The co-ordination time interval of 0·5 second has been taken in the above example. It may become necessary to calculate this interval more accurately in case the time of operation of the relay at the location next to the source may be too long. The procedure for calculating the co-ordination time interval is explained in **6.4.2**.

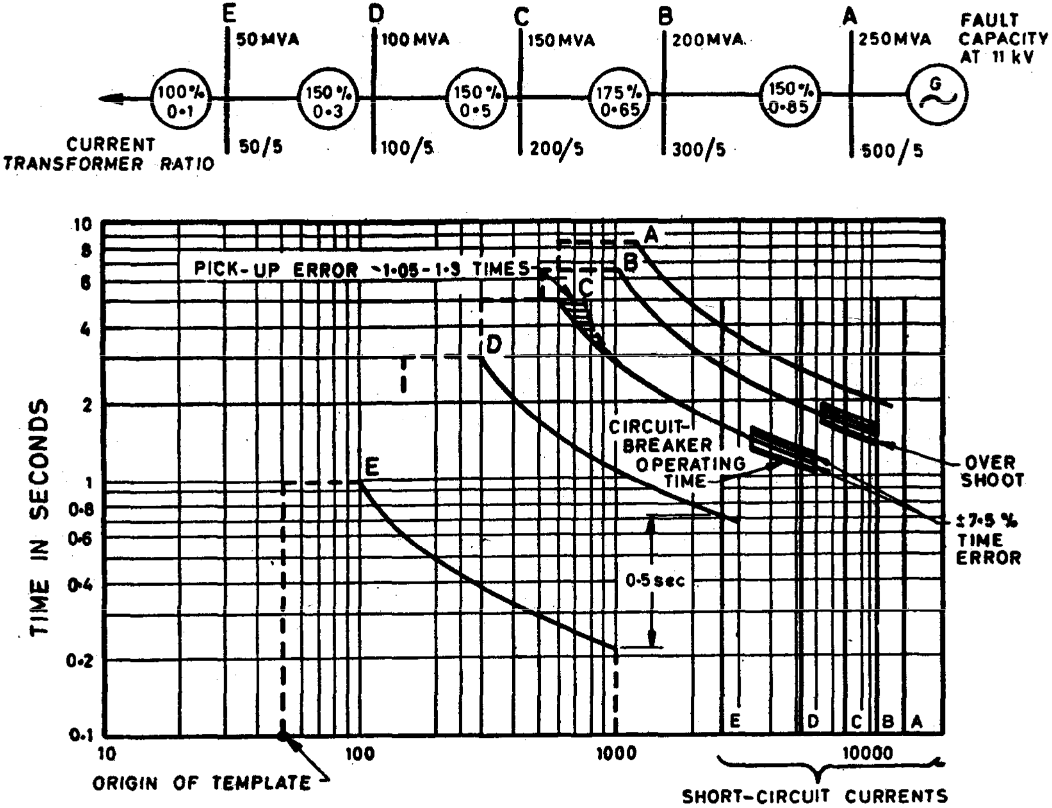
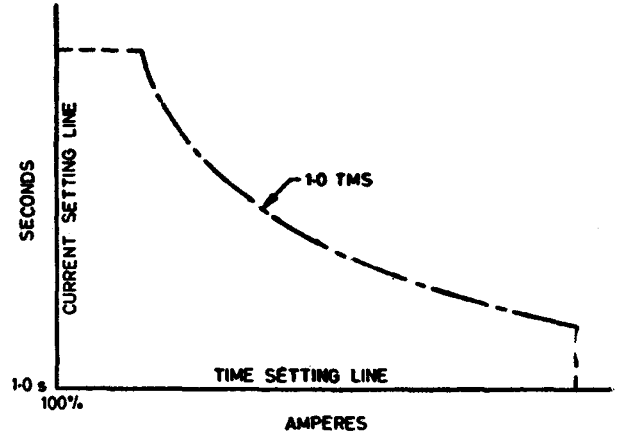


Fig. 12 Setting and Co-ordination of IDMTL Relays for a Radial Circuit Fed at One End Only



TMS = Time setting multiplier (or time multiplier scale)

FIG. 13 TEMPLATE FOR SETTING IDMTL RELAYS

It may not be too much to add that a check should be made regarding the ability of the cables to withstand the short-circuit current for the duration of the time of the operation of the relays. Data giving the short-circuit withstand ability of the cables should be obtained from the manufacturers.

The example given above is a simple one in order to illustrate how selectivity is achieved with standard IDMTL relays. But in actual practice the networks are more complex. The networks should be divided into sections consisting of 4 or 5 stations and the principles enunciated above be applied. It may be necessary to do the exercise a few times before arriving at the final settings. This is particularly true for loop circuits and especially if there is in-feed at a number of locations. The trial and error methods is the only way to proceed with such circuits. However, the use of template after some experience becomes instinctive and the length of time involved in settings is reduced to a very little percentage of that normally required for obtaining them by arithmetical methods. The template method is of definite advantage where different types of relays are used.

6.4.3.2 *Setting and co-ordination of IDMTL relays — earth-fault relays* — The method of setting earth-fault relays is the same as explained in **6.4.3.1**. Since no current flows through the earth-fault relays in the systems normally having balanced 3-phase load conditions, the earth-fault relays may have current settings lower than those generally used for phase-fault relays. However, in distribution networks single phase loads are likely to be present and the effect of expected unbalanced currents in the neutral must be taken

into account in choosing the current setting. The earth-fault relays may also be set to trip faster than phase-fault relays because firstly the later have to be selective with the phase-fault relays next to their location and also because of the fact that the earth-fault relay cannot see the fault current through star-delta or delta-star power transformers.

The earth-fault relays operate satisfactorily over their entire tap range provided current transformers have high accuracy. The relay may not, however, operate on the lowest tap if it is connected to bushing type current transformers of low turns ratio. This is because the ratio accuracy of the bushing current transformers breaks down on account of high impedance of the relay at its lowest current tap. If on checking it is found that the relay may not operate, it is preferable to use a higher current tap on the relay or the current transformer.

The earth-fault relays may also maloperate during a phase fault because of the current transformer errors. It has been found that the magnitude of the current error may be as much as 30 to 40 percent or even more. One solution may be to increase the earth-fault current setting but this may result in greater damage during an earth fault. The better alternative is to select the minimum relay pick-up consistent with positive operation and then prevent maloperation by giving a one step slower operating time.

In systems where current limiting impedances are used in the neutral of generator or power transformer the application of earth-fault relays needs careful consideration. The more sensitive the earth-fault relay the greater possibility there is of its maloperation on account of current transformer error currents. Secondly, the effect of limiting earth current is to reduce the difference in magnitude of earth-fault currents at different locations. If this difference is small then the inverse-time characteristic is of little use and selectivity should be obtained on the basis of time alone.

6.5 Setting of Very-Inverse Overcurrent Relays

6.5.1 Figure 14 shows 4 substations on a radial feeder. The fault levels and the current transformer ratios at the substations are indicated. It may be seen that the fault levels at the consecutive stations are of the order of 4 : 7 or 1 : 2. This permits the best use of very-inverse relays because the time-current characteristic of very-inverse relays is such that the time of operation is nearly halved when the fault current happens to be between 4 to 7 times of the plug setting multiplier, that is, the inverse part of the characteristic is made use of.

6.5.2 Another advantage of using these relays is that the co-ordinating time interval between the relays at two locations can be brought down to 0·35 seconds which can be explained as below:

a) Circuit breaker opening time =0·16 second.

b) Overshoot =0·05 second.

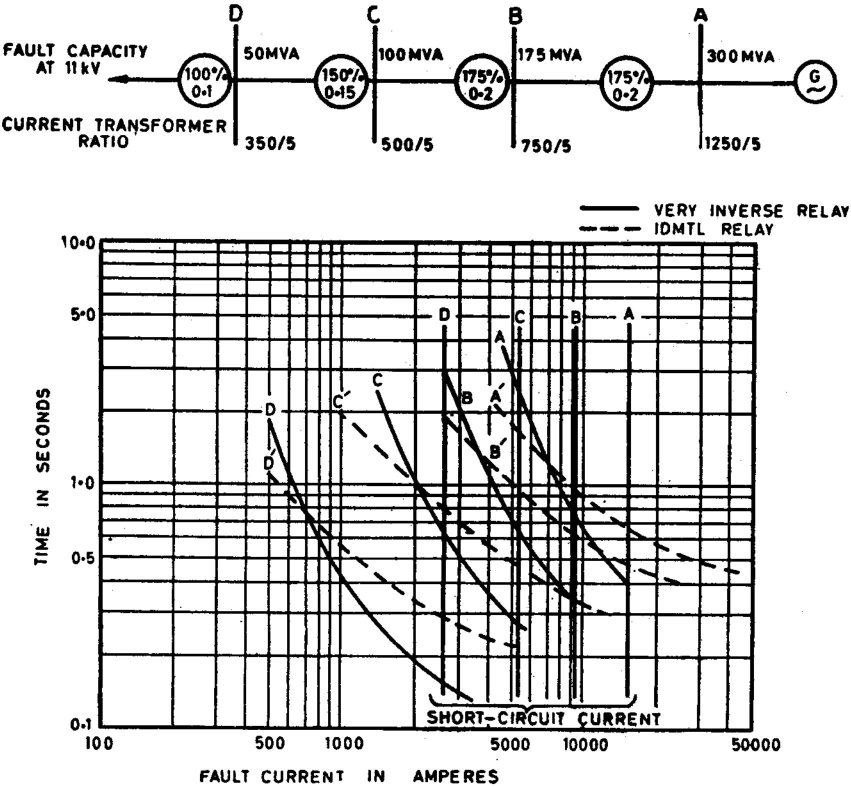


FIG. 14 SETTING OF VERY-INVERSE RELAYS

c) Relay errors, that is, positive at one location and negative at the other location:
   1) at 4 times relay setting and 0·2 time setting multiplier at 12·5 percent error =0·084 second,
   2) at 7 times relay setting and 0·2 time setting multiplier at 7·5 percent error =0·027 second.

   Total time =0·16+0·05+0·084+0·027
   =0·321 second.

The co-ordinating time interval of 0·35 second thus provides reasonable safety margin.

6.5.3 The settings and the co-ordinations of the relays are obtained by the template method, already explained. To make the difference between the

use of very-inverse and IDMTL relays obvious, dotted curves on Fig. 14 show the operating time characteristics of the later at various relay locations, using the same settings for both the relays. The IDMTL relays at *B* and *A* do not allow sufficient time for discrimination. Also, the minimum time of operation of the two types of relays (for a fault in its own zone) will be as follows:

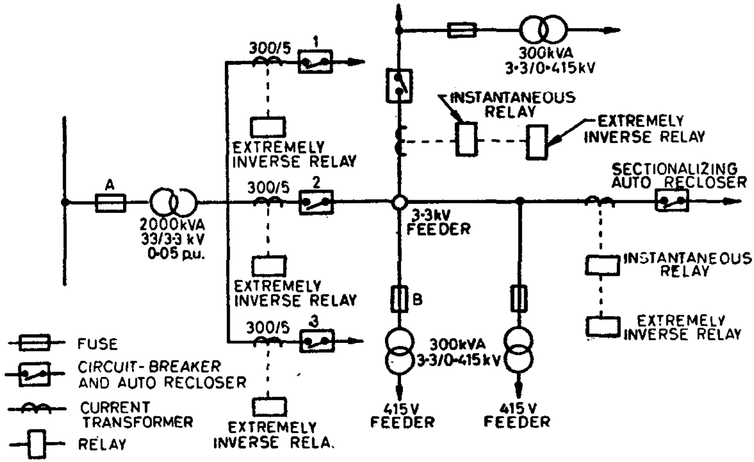
	Very-Inverse *Second*	*IDMTL* *Second*
D	0·15	0·27
C	0·26	0·46
B	0·36	0·63
A	0·4	0·7

6.5.4 An approximate method is also sometimes used to achieve co-ordination. The same time setting multiplier is used at all the relay locations. Settings of the various relays are selected so that the fault current at its own location and those at the location before it are 7 and 4 times respectively of the plug setting multiplier.

6.6 Setting of Extremely-Inverse Relays

6.6.1 In distribution systems, the operation of the feeder circuit breaker has to be co-ordinated with the fuses on the high voltage side of distribution transformers. For simple radial distribution circuits, it is enough to draw the time-current characteristic of the extremely-inverse relay and the fuses making provision for a co-ordinating time interval of 0·4 to 0·5 second. However, it is normal practice to sectionalize the distribution circuits with fuses or reclosers or both so as to interrupt a section of the distribution circuit only in case of persistent faults on a particular section. An instantaneous overcurrent attachment is added to the extremely-inverse relay so that the auto-reclosers operate before the fuses are blown on transient faults. The instantaneous overcurrent relay is removed from service as the first reclosure takes place. If the fault persists the fuse blows before the extremely-inverse relay operates. As the majority of the faults in distribution systems are transient in nature, unnecessary blowing of fuses is thus avoided. Figure 15A shows a distribution system with fuses and circuit breaker with auto-reclosing facility and Fig. 15B shows the grading. The extremely-inverse relay operating the circuit breaker 2 and the fuses *A* and *B* on either side of the feeder transformer are time graded providing a co-ordinating time interval of 0·4 second between the operating time of the fuses and the relay.

6.6.2 To set extremely-inverse relays on distribution systems in which the initial load current is many times the normal full load current when it is re-energized after an outage, that is, cold load restoration it is useful to have the load current versus time curve of the distribution system. Figure 16 shows a typical curve. Assuming that the overcurrent element is set to operate at 200 percent of full load, the curve in Fig. 16 shows that the



$$\text{Full-load current of main transformer} = \frac{2\,000}{\sqrt{3} \times 33} \begin{array}{l} = 35 \text{ A on } 33 \text{ kV side} \\ = 350 \text{ A on } 3{\cdot}3 \text{ kV side} \end{array}$$

Fuse *A* — Rating = 100 A, 33 kV HRC Fuse

$$\text{Fault current at secondary} = \frac{350}{0{\cdot}05} = 7\,000 \text{ A}$$

$$\text{Full load current of distribution transformers} = \frac{300}{\sqrt{3} \times 3{\cdot}3} = 52 \text{ A}$$

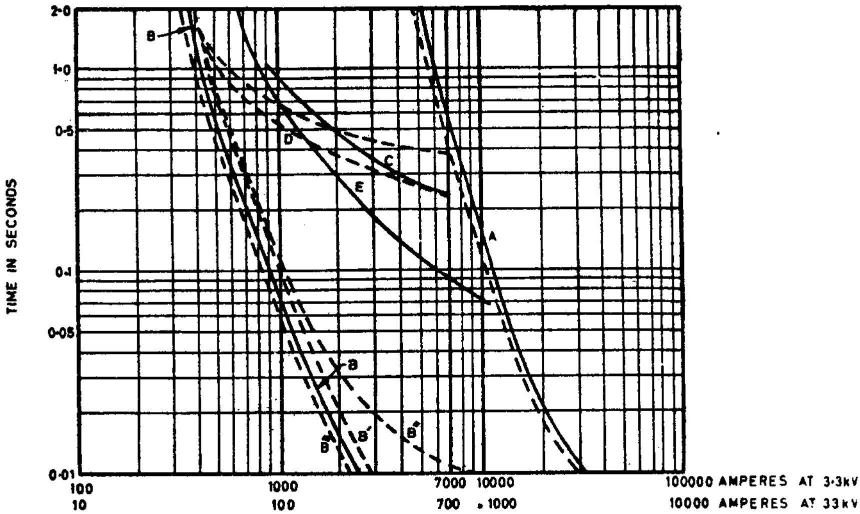
Fuse *B* — Rating = 75 A, 3·3 kV HRC Fuse

Fault current at B = 1 050 A

15A Circuit Diagram

FIG. 15 EXTREMELY-INVERSE RELAYS USED FOR CIRCUIT-BREAKERS WITH AUTO-RECLOSING FACILITY IN CONJUNCTION WITH FUSES FOR DISTRIBUTION NETWORKS

current higher than the setting persists for about 2·3 seconds. The average value of the current over this period should be worked out, which in this example is about 170 percent of the relay setting. Therefore, the time setting multiplier is selected so that the relay operating time at 1·7 times the plug setting multiplier is more than 2·3 seconds. In practice, the instantaneous overcurrent relay will invariably operate after prolonged outages. The trip circuit of the instantaneous overcurrent relay is opened manually to allow for the load currents to fall below its setting.



A = 100 A, 33 kV fuse characteristic
B = 75 A, 3·3 kV fuse characteristic
C = Circuit-breaker time-current characteristic
D = IDMTL overcurrent relay characteristic
E = Extremely-inverse overcurrent relay characteristic
Current setting 100 percent
Time multiplier 0·2

Fuse Tolerances

B' = Manufacturing tolerance
B'' = Arcing time tolerance
B''' = Minus 10 percent tolerance for possible fuse damage

15B Grading

FIG. 15 EXTREMELY-INVERSE RELAYS USED FOR CIRCUIT-BREAKERS WITH AUTO-RECLOSING FACILITY IN CONJUNCTION WITH FUSES FOR DISTRIBUTION NETWORKS

6.7 Overcurrent Relays with ac Tripping

6.7.1 Overcurrent relays with ac tripping are also available for use at substations where provision of battery and the associated charging equipment is rather uneconomical. In one type, a tripping reactor is connected in series with the relay coil in the current transformer secondary circuit. The tripping coil of the circuit breaker is connected across this tripping reactor

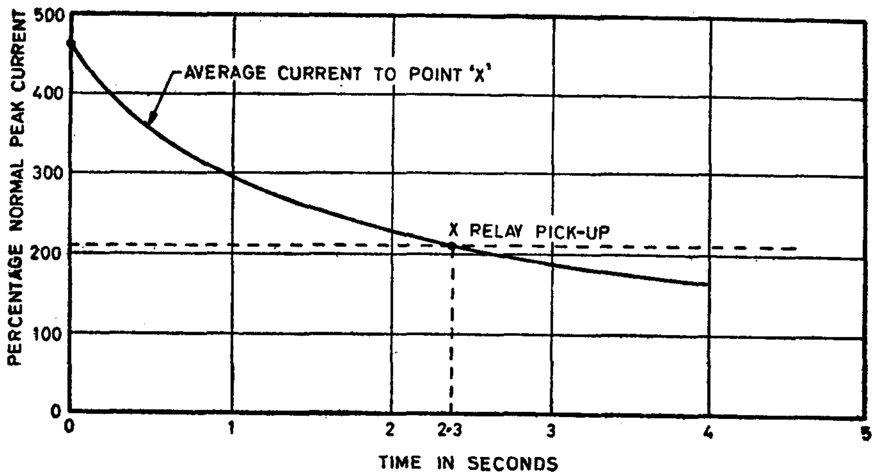


FIG. 16 COLD LOAD RESTORATION CURVE

through the contact of the overcurrent relay. Figure 17 shows the connections for a triple pole overcurrent relay. During a short-circuit, voltage drop through the reactor is sufficient to operate the trip coil when the overcurrent relay closes its contacts. However, this method is effective only if the short circuit current is equal to or higher than the rated load current because at low-fault currents the current transformers are unable to produce sufficient voltage. Saturation of the tripping reactor limits the voltage to a safe value at high-fault currents. Shunt resistors (not shown in the diagram) are used to hold down the peak value of this voltage. Reliable tripping can be ensured for both phase and earth faults.

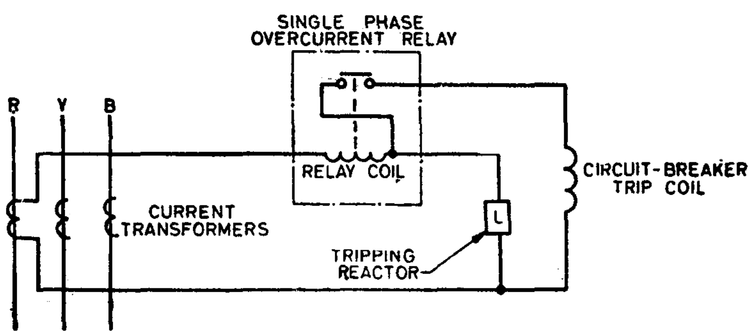


FIG. 17 TYPICAL WIRING DIAGRAM OF ac TRIPPING WITH AN OVERCURRENT RELAY AND A TRIPPING REACTOR

6.7.2 The circuit of another type of ac tripping overcurrent relay is shown in Fig. 18. Internally it has an instantaneous unit which opens a normally closed contact when the main relay closes its normally open contact. This allows the fault current to flow through the trip coil which operates the circuit breaker. Before using this relay the following points should be checked:

a) The current transformers have sufficient output at the minimum setting of the relay to operate the trip coil.

b) The current rating of the normally closed contact of the instantaneous unit should be ascertained from the manufacturers. The current flowing through it should be limited if necessary by external resistance.

NOTE — An example for working out the values of the series resistor and the saturating choke is given in **6.7.4**.

c) The voltage which appears across the contacts is also sometimes a limitation and its value should be ascertained from the manufacturer.

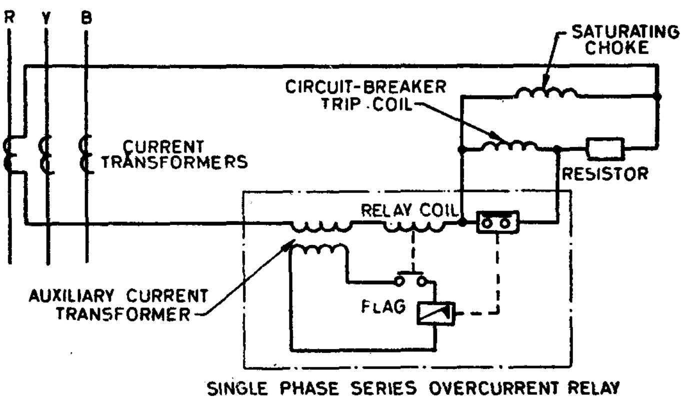


FIG. 18 TYPICAL WIRING DIAGRAM OF ac SERIES TRIPPING OVERCURRENT RELAY

6.7.3 Alternate current tripping relays are basically inferior because of their lesser sensitivity. Their contacts require more maintenance because of the severe duty imposed on them. The burden imposed on the current transformer is high and because of this, accurate metering cannot be provided from the same current transformer.

6.7.4 *Example Showing the Calculation of Choke Impedance and Resistance*

6.7.4.1 To determine the values of choke impedance and resistance the following data should be collected:

a) The knee point voltage and the maximum voltages of the current transformers,

b) The impedance of the trip coil at the maximum and minimum tripping currents in both the plunger up and plunger down positions,

c) The secondary resistance of the current transformers and the leads,

d) The burden of the relay, and

e) Fault currents in the primary circuit.

6.7.4.2 It is assumed that a series trip IDMTL relay having a current setting of 50 to 200 percent of 5 A is used. It has an impedance of 0·025 Ω at 20 times the tap current. The normally closed contacts can break a current of 150 A and withstand 150 V. The other data is as follows:

Current transformers:

Ratio	= 100/5
Knee point voltage	= 36 V
Maximum voltage developed by current transformers	= 50 V
Secondary resistance	= 0·12 Ω
Lead resistance	= 0·01 Ω
Circuit-breaker rupturing capacity at 11 kV	= 250 MVA
Maximum phase-fault current	$= \dfrac{250 \times 10^6}{11\,000 \times \sqrt{3}}$
	= 13 100 A

Trip coil:

Setting	= 30 percent (1·5 A)
Impedance of the coil with plunger at the beginning of the stroke	= 3·56 Ω
Impedance of the coil with plunger at the end of the stroke at minimum tripping current	= 5·35 Ω

6.7.4.3 *Series resistor* — The value of the current through the resistor should be limited to 150 A.

The ohmic value of this resistor is given by:

$$R = \frac{V}{150} - (R_1 + R_2 + R_3)\ \Omega$$

where

R = resistance of the series resistor in hms,

V = maximum rms voltage developed by the current transformer,

R_1 = secondary resistance of the current transformer in ohms,

R_2 = resistance of the relay in ohms, and

R_3 = resistance of the leads in ohms.

Substituting the values given in **6.7.4.2**:

$$R = \left[\frac{50}{150} - (0{\cdot}12+0{\cdot}025+0{\cdot}01)\right] = 0{\cdot}18\ \Omega.$$

This value holds provided the maximum voltage developed by the current transformer does not exceed 50 V.

6.7.4.4 *Saturation choke* — The unsaturated value of the impedance of the choke is calculated for the minimum operating value of the trip coil and the minimum relay setting. This is given by:

$$Z_1 = \frac{I_1\ (Z_T+R)}{1{\cdot}2\ (I_2-I_1)}$$

where

Z_1 = unsaturated value of the impedance of the choke in ohms,
I_1 = minimum trip coil setting in amperes,
Z_T = trip coil impedance at minimum trip coil setting and with plunger up in ohms,
R = resistance of the series resistor in ohms, and
I_2 = minimum relay setting in amperes.

Substituting the values given in **6.7.4.2**:

$$Z_1 = \frac{1{\cdot}5\times(5{\cdot}35+0{\cdot}18)}{1{\cdot}2\times(2{\cdot}5-1{\cdot}5)} = 5{\cdot}53\ \Omega.$$

The saturated value of the choke impedance at 20 times the relay setting with current transformer voltage at knee point is given by:

$$Z_2 = \frac{R\left(\dfrac{V}{I} - R_x\right)}{R + R_x - \dfrac{V}{I}}$$

where

Z_2 = saturated value of the impedance of the choke in ohms;
R = the resistance of the series resistor in ohms;
V = knee point voltage of the current transformer;
I^* = 20 times the maximum relay setting current; and
R_x = the combined secondary resistance of the current transformer, leads and the relay in ohms.

Substituting the values, we get:

$$Z_2 = \frac{0{\cdot}18\times\left(\dfrac{36}{20\times10} - 0{\cdot}155\right)}{0{\cdot}18 + 0{\cdot}155 - \dfrac{36}{20\times10}} = 0{\cdot}029\ \Omega.$$

The ratio of the unsaturated to saturated choke impedance works out to $\frac{5 \cdot 53}{0 \cdot 029}$, that is, roughly $\frac{190}{1}$. In practice, a ratio of 40 : 1 is possible, that is, the saturated impedance of about 0·138 Ω is attainable. Assuming that the relay is set at 200 percent and the saturated choke impedance of 0·138 Ω is used, the relay will remain accurate up to 15·5 times the maximum setting. However, if the relay is set at 100 percent it will remain accurate well over 20 times the setting.

6.8 Core Balance Earth-Fault Protection

6.8.1 This form of protection consists of a ring core current transformer which is designed to pass over 3-core cables. The output from this current transformer is used to energize a current operated relay as shown in Fig. 19. This arrangement provides very sensitive earth-fault protection and is recommended for industrial and distribution feeders in mines. The earth-fault settings as low as 5 A (primary) may be obtained with this protection. The protection is normally quite stable for faults in other cables adjacent to the core balance current transformer and for phase faults in the protected cable.

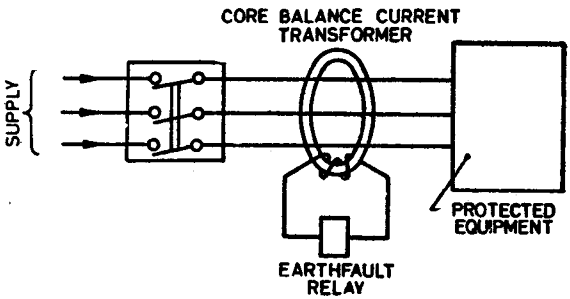


FIG. 19 EARTH-FAULT PROTECTION USING CORE BALANCE CURRENT TRANSFORMER

6.8.2 This protection may be used to give indication of earth faults in cable networks (*see* Fig. 20). This arrangement assists in rapid location of feeder faults. A cable which is feeding an earth fault, energizes all the relays between the supply and the fault, permitting the faulty section to be readily indentified. The core balance current transformer is designed to saturate during heavy earth faults, providing thermal protection to the relay by limiting the secondary current.

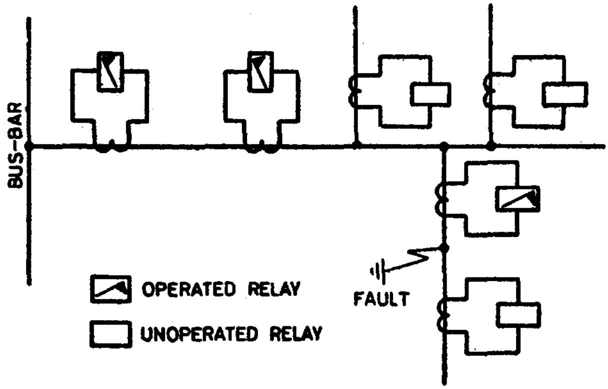


FIG. 20 INDICATION OF EARTH FAULTS USING CORE BALANCE CURRENT TRANSFORMER

7. SETTING AND CO-ORDINATION OF OVERCURRENT RELAYS FOR TRANSFORMERS

7.1 General — As a rule, differential schemes are used for the main protection of large transformers and overcurrent relays provide the back-up protection. Generally for smaller transformers, that is, up to 5 MVA, for economic reasons, overcurrent relays are used as main protection. The impedance of the transformers gives a sufficient fault current differential on the primary and secondary sides. This fact is made use of, especially on transformer feeders to achieve high speed tripping for faults up to the terminals of the secondary windings by using instantaneous overcurrent relays.

7.1.1 Phase-fault protection for transformers is relatively simple but the earth faults need careful analysis. The following factors should be kept in mind while applying the overcurrent relays for the protection (main or back-up) of transformers:

a) Magnetizing in-rush current—The IDMTL relays generally have sufficient time delay to ensure against false operation. The setting of the instantaneous overcurrent relays should be carefully chosen.

b) Connections of the transformer delta-star connections give different current distribution on the primary and the secondary side for phase-to-phase faults. If only two overcurrent relays are used for phase-fault protection, the lower current should be used for the current setting, and the higher current for the time setting.

When the primary windings of the transformer are delta connected or have an unearthed star point, an earth-fault relay (connected in

the residual circuit of 3-current transformers) on the primary side operates for internal faults on the primary windings, only because earth faults on the secondary windings do not produce zero phase sequence currents on the primary side. The restricted earth-fault protection (discussed in detail in **7.4**) may then be used for high speed tripping for faults on the star-connected earthed secondary winding of the transformer.

c) Primary full load current.

7.1.2 For 3-winding transformers IDMTL relays on each winding shall be required if all the 3 windings are connected to sources of power.

7.1.3 The current transformers on the high voltage side of a transformer are of comparatively low ratio but are of ring pattern because they have to withstand heavy fault currents. Their rated output and impedances are low. This consideration is of particular importance in the case of earth-fault relays in the residual circuit of 3-current transformers as the shunting effect of the low impedance secondaries in the healthy phases has a considerable effect upon the fault setting of the relay.

7.2 Settings of Overcurrent Relays for Transformers and Transformer Feeders

7.2.1 *IDMTL Overcurrent Relays* — IDMTL overcurrent relays are generally set at 125 percent of the transformer rating. The time delay of the IDMTL relays should be sufficient to override normal overload swings or magnetizing in-rush currents. If there are several transformers on the main feeder without individual primary side fault protection, the relay setting of 1·25 times the total full-load rating of all the transformers is ample. However, it should be ensured that this setting is adequate to clear the fault on the secondary side of the smallest transformer. If the transformers have their individual protection then the overcurrent relays on the main feeder should be set to co-ordinate with the protection on the transformer.

7.2.2 *Setting of Instantaneous Overcurrent Relays*

7.2.2.1 The setting of the instantaneous overcurrent relay on the primary side of the transformer should be a little above asymetrical value of the fault current for 3-phase fault on the secondary terminals of the transformer. As far as possible the relays with a low transient overreach should be used or the effect of the overreach should be taken account of. The setting is usually high enough to override the magnetizing in-rush at the time of energizing the transformer.

7.2.2.2 On a main feeder supplying several transformers, the current setting depends on the total magnetizing in-rush of the transformer banks and a setting of 10 to 15 times the full-load rating is chosen for the instantaneous relay.

7.2.2.3 Where the application dictates that overcurrent relays should be

set at about 4 to 5 times the full load, a time delay is required to avoid maloperation.

7.3 External Fault Back-Up Protection — Inverse time relays with a long time delay are commonly used to give a final back-up protection for isolating the transformer or bus bar from the rest of the system if the earth fault persists and the other earth-fault relays do not clear it. The relay is connected to a current transformer in the neutral of the transformer. If there is a neutral grounding resistor or an earthing transformer, the relay is set for long time delay to permit the flow of current up to the thermal limit of the resistor or an earthing transformer, for example, if the resistor is rated for 10 seconds the relay would be set to operate between 7 to 10 seconds.

7.4 Earth-Fault Protection of Transformers and Transformer Feeders

7.4.1 *Earth-Fault Protection for Delta or Unearthed Star-Connected Transformer*

7.4.1.1 An earth-fault relay connected in the residual circuit of the line current transformers gives protection against earth faults on the delta or unearthed star-connected windings of the transformers. As already stated in **7.1**, earth faults on the secondary side of the transformer are not reflected on the primary side. Thus it is possible to obtain very low fault settings (for example, 10 percent of the full-load rating) and high speed tripping. The relay should be of the high impedance type to prevent wrong operation on false residual current from the 3-line current transformers during a heavy external fault between phases or during magnetizing current in-rush. Alternatively, a stabilizing resistor is introduced to increase the impedance of the relay coil circuit. This is seldom necessary for IDMTL overcurrent relays which have an inherent time delay but is essential for an instantaneous attracted armature type overcurrent relay.

7.4.1.2 It may also be seen that an earth fault on one line energizes only one of the 3-line current transformers. The secondary current thus produced gets divided in the relay coil and the secondary windings of the unfaulted line current transformers. Therefore, the primary fault current required to operate the relay at the minimum current setting should be sufficient to allow for the shunting effect caused by the two healthy secondary windings of the current transformers. The primary current which will operate the relay is given by:

$$I_p = (3\ I_M + I_R) \times N$$

where

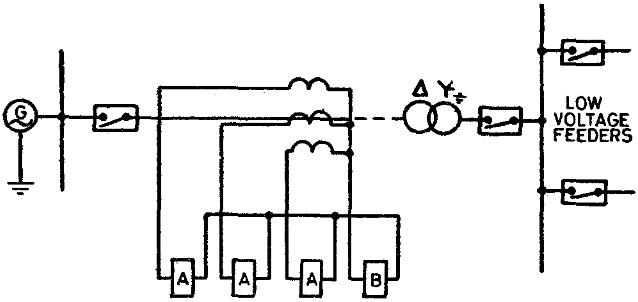
I_p = primary current,

I_M = magnetizing current of the current transformer at a voltage $V = I_R \times$ impedance of the relay coil,

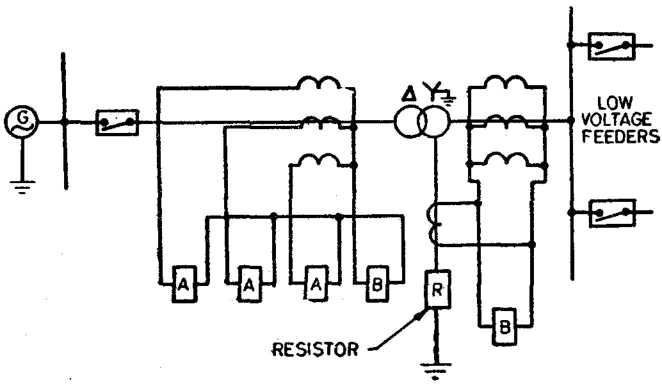
I_R = operating current at the minimum setting of the relay, and

N = current transformer ratio.

7.4.1.3 Figure 21 shows an earth-fault relay connected in the residual circuit of 3-current transformers for a delta-connected primary winding of the transformer.



21A Protection Suitable for Single Delta/Star Transformer or Transformer Feeder



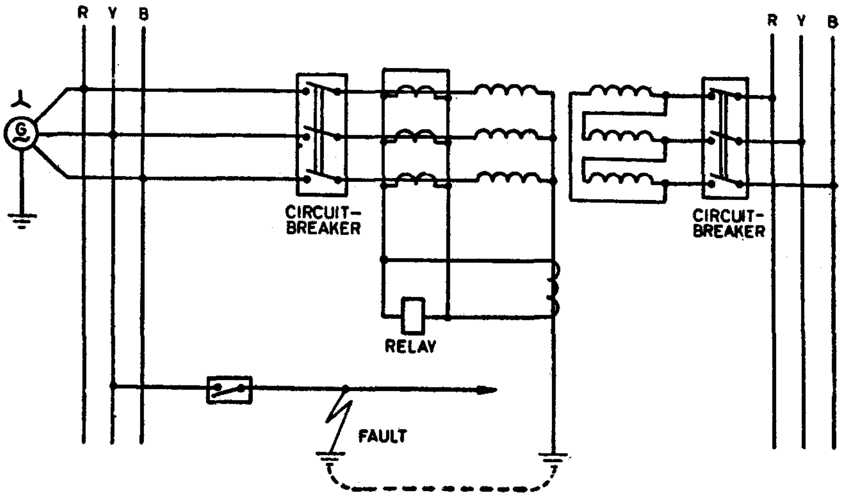
21B Protection Suitable for Single Delta/Star Transformer or Transformer Feeder with an Adjacent Transformer

A = Non-directional overcurrent relay
B = Non-directional restricted earth-fault relay

FIG. 21 CONNECTION OF EARTH-FAULT RELAY IN THE RESIDUAL CIRCUIT OF THREE CURRENT TRANSFORMERS FOR PROTECTION OF TRANSFORMER WITH DELTA CONNECTED PRIMARY WINDING

7.4.2 *Restricted Earth-Fault Protection* — The star-connected earthed winding of a transformer feeder may be protected by a restricted earth-fault relay which will operate for earth faults in its winding only, The connections for such a relay are shown in Fig. 22. It is basically a differential connection

in which a current transformer in the neutral of the earthed star winding is balanced against the residual current of the 3-line current transformers. Very sensitive relays may be used to give high speed tripping. The shunting effect of the healthy current transformers and the stability requirements during external fault conditions, already detailed in **7.4.1**, apply to the restricted earth-fault protective system also.



NOTE — Current through the Relay $I_{Res} = I_0 - \frac{3I_0}{3} = 0$

FIG. 22 CONNECTIONS FOR RESTRICTED EARTH-FAULT PROTECTION FOR TRANSFORMER OR SHORT TRANSFORMER FEEDER

Usually the total impedance of the relay and the series resistor is low enough to prevent the current transformers from developing voltages above 2 kV rms during the most severe internal fault. However, in some applications if the voltage is higher than 2 kV rms a non-linear resistor may be required to limit the voltage and is connected across the relay and the stabilizing resistor.

7.4.2.1 The stabilizing resistor is chosen to ensure that the voltage developed under maximum fault current conditions does not operate the relay. An example giving the calculations for the stabilizing resistor is given below:

Relay:

Type	Instantaneous earth-fault relay
Current setting range	10 to 40 percent of 5 A
Burden	1·0 VA at current setting

Current transformers:

Ratio	= 100/5
Knee-point voltage	= 36 V
Secondary resistance (R_{CT})	= 0·12 Ω

Lead resistance (R_1) = 0·01 Ω

Maximum phase-to-phase fault current (rms symmetrical value)	= 2 000 A
Minimum relay current setting (I_r)	= 0·5 A
Impedance of the relay at minimum setting	$= \frac{1}{(0{\cdot}5)^2}$
	= 4Ω

Assumed that the resistive component of the above is 1Ω.

Minimum knee-point voltage (V_{kp}) is given by the formula:

$$V_{kp} = 2\ I_f\ (R_{CT}+R_1)$$
$$= 2\ I_r\ R_r$$

where

$$V_{kp} = 2 \times 2\ 000 \times \frac{5}{100}(0{\cdot}12 + 0{\cdot}01)$$
$$= 26\ \text{V}$$

I_f = equivalent secondary pilot current of maximum phase-to-phase fault, and

R_r = total resistance of relay circuit.

If S=stabilizing resistance, total resistance of relay circuit (R_r) =(S+4)Ω

or $0{\cdot}5 \times (S+4) = \frac{26}{2}$ or $S = 22\Omega$

A variable (or tapped) stabilizing resistance with a value of 0 to 30Ω will ensure that the current transformers meet the minimum knee-point requirements at the higher current settings also. The effective primary fault current setting (I_s) for a given relay current setting (I_r) is given by the formula:

$$I_s = (3\ I_M+I_r) \times n$$

where

I_M = magnetizing current of the current transformer at voltage $I_r \times R_r$.

In the above example,

Relay setting I_r	= 0·5 A (10 percent setting)
Magnetizing current at (0·5×26) V	= 0·44 A
∴ Effective primary fault current setting I_s	$= (3 \times 0{\cdot}44 + 0{\cdot}5) \times \frac{100}{5}$
	= 36·5 A
	= 36·5 percent (using 100/5 current transformers)

7.4.3 *Overcurrent Protection of Unit (or Station) Transformers* — The application of overcurrent relays for the protection of unit transformers is different from that for power transformers for the following reasons:

a) The unit transformer has very small rating compared to that of the main transformer, for example, for a hydro-generator its rating is about 1 percent of the rating of the main transformer. Therefore, the impedance of the station transformer is so high that the fault currents on the primary and secondary sides differ greatly in their magnitudes.

b) To provide adequate short-circuit protection and reasonable overload protection of the station transformer, low ratio current transformers which will saturate for faults on the high voltage side will have to be used but care has to be taken that their ratio is not so low as to cause maldiscrimination between protection on the high voltage and low voltage sides of the transformers for faults on the low voltage circuits.

c) The thermal rating of the relay should be considered to protect its coils, if too large a current flows through it during faults within the transformer.

In view of the above considerations, an IDMTL overcurrent relay is used to provide overload and back-up protection for faults beyond the secondary terminals of the transformer. It is supplemented by an instantaneous overcurrent relay with low transient overreach set to operate for faults within the transformer and on the primary side.

7.4.3.1 Figure 23 shows a unit transformer and an example is given below to make clear the application of the overcurrent protection:

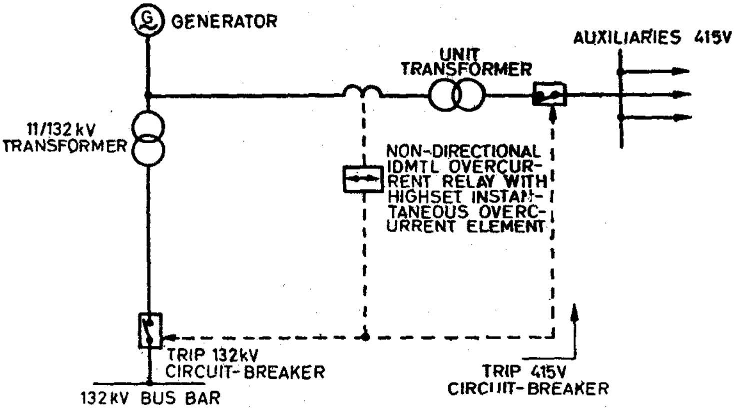


FIG. 23 PROTECTION OF A UNIT TRANSFORMER

Unit transformer:

Rating	= 300 kVA
Ratio	= 11/0·415 kV
Impedance	= 5 percent
Vector group	= *Dy* 11

System fault level = 250 MVA at 11 kV

Current transformers:

Ratio	= 20/5
Class	= 15 P5
Knee-point voltage	= 40 V
Secondary resistance	= 0·16Ω

Relay:

IDMTL overcurrent unit:

Current setting range	= 50 to 100 percent of 5A
Burden	= 1·0 VA
Impedance at 20 times current setting	= 0·015Ω

Instantaneous overcurrent unit:

Current setting range = 500 to 2 000 percent of 5A

Current transformer lead resistance = 0·1Ω

If the source impedance (Z_s) is 10 percent on 17 MVA base, impedance (Z_1) of unit transformer on 17 MVA

$$= \frac{17\,000}{300} \times 0{\cdot}05$$

$$= 300 \text{ percent}$$

Ratio of $\dfrac{\text{fault current on high voltage side of transformer}}{\text{fault current on low voltage side}}$

$$= \frac{Z_s + Z_1}{Z_s} = \frac{(10+300)}{10} = 31$$

Fault current on high voltage side (for a fault on the low voltage side)

$$= \frac{17\,000}{3{\cdot}1 \times \sqrt{3} \times 11}$$

$$= 300 \text{ A}$$

Setting of instantaneous overcurrent relay:

A current setting of 125 percent of 300 A is chosen considering 25 percent overreach, that is, a setting of 380 A may be given to this unit.

$$\therefore \text{Current setting} = \frac{380}{20} \times 100$$
$$= 1\,900 \text{ percent}$$

Setting of IDMTL overcurrent relay:

Full-load current of unit transformer

$$= \frac{300}{\sqrt{3} \times 11} = 15{\cdot}7 \text{ A}$$

Choosing a setting of 16 A for the relay the 80 percent tap may be used. The IDMTL relay will then give protection for a short-circuit current of $\frac{380}{16} = 24$ times current setting and less.

7.4.4 *Protection of Transformers in Parallel* — When the transformer is operating in parallel with other units, *in addition* to provision of the overcurrent relay (*see* **7.1**) and the earth-fault relay (*see* **7.4.1.3**), it will be necessary to have directional overcurrent and earth-fault relays on the secondary side to prevent the healthy section in parallel feeding into the faulty section, although isolated by the operation of the overcurrent relay on the feeding (primary) side. The principles of directional overcurrent relays are covered in **8**.

7.4.4.1 *Overcurrent protection* — Figure 24 shows a typical overload protection scheme for transformers operating in parallel, using overcurrent relays with both, non-directional and directional features. By having directional relay in each of the parallel transformer circuits in addition to non-directional relays, the possibility of feeding into the fault (phase-to-phase) through the alternate parallel circuit (feed-back) is eliminated by the operation of the directional overcurrent relay (having faster setting) thereby isolating the faulty section. Thus both the non-directional overcurrent relay on the primary side and the directional overcurrent relay, together, isolate the faulty transformer section without interrupting the other transformer section in parallel, thereby achieving a proper discrimination.

In the above typical protection circuit, the current coils of both, the non-directional and the directional relays (on the secondary side) are connected in series. The directional relay being power operated has in addition, voltage coils fed by a voltage transformer. The resistances connected in series with the voltage coils cause shifting of voltage vector by 45° at which the maximum torque is obtainable. If the power flows in the normal direction, the torque on the directional element is such as to close the relay contact thereby shunting the dc time-delay contactor,

preventing the relay tripping operation. But still the circuit-breaker will be tripped by the delayed contact of the non-directional relay. If, however, the power flow is in the reverse direction (due to feed-back), the relay contact of the directional relay will not be closed and the dc time-delay contactor will not be shunted. The circuit-breaker will trip after set time delay of the contactor. The time setting for directional relay is lower (about 0·2 second) than that for non-directional relay (about 0·4 second).

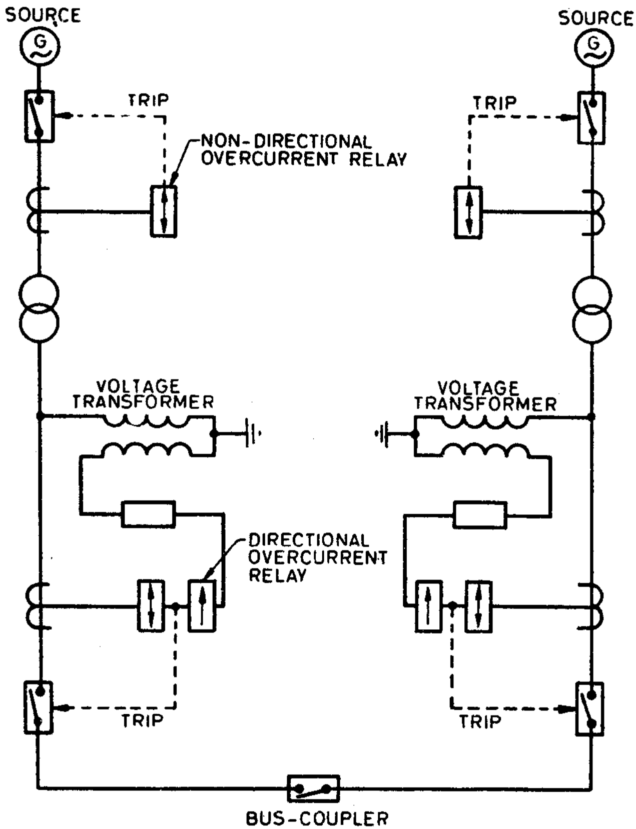


FIG. 24 OVERLOAD PROTECTION OF TRANSFORMER IN PARALLEL

7.4.4.2 *Earth-fault protection* — The above protection is adequate for phase-to-phase fault. In addition, earth-fault protection would be

necessary as shown in Fig. 25 (showing the secondary side only). The non-directional or directional earth-fault relay is used, which is power operated having a voltage coil in addition to current coil. While the non-directional relay is connected in the neutral circuit of the line current transformers, the directional relay is connected across the open delta winding of the voltage transformers. Normally, there is no voltage across the open delta winding since the 3 voltages are balanced. However, in case of earth fault on any one phase, voltage will appear across the open delta, causing the relay to operate. If the power flow due to earth fault is in the normal direction, the movement of the relay contact is to close the contact of the non-directional element. If, however, the power flow is in the reverse direction (due to feed-back), the relay contact will move so as to close the contact of the directional element. The time setting for the directional relay is very low (about 0·2 second) compared to that for non-directional relay (about 2 seconds).

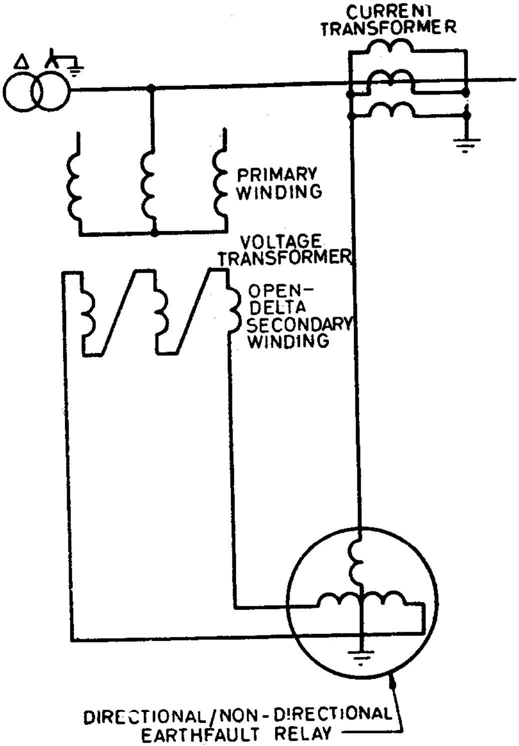
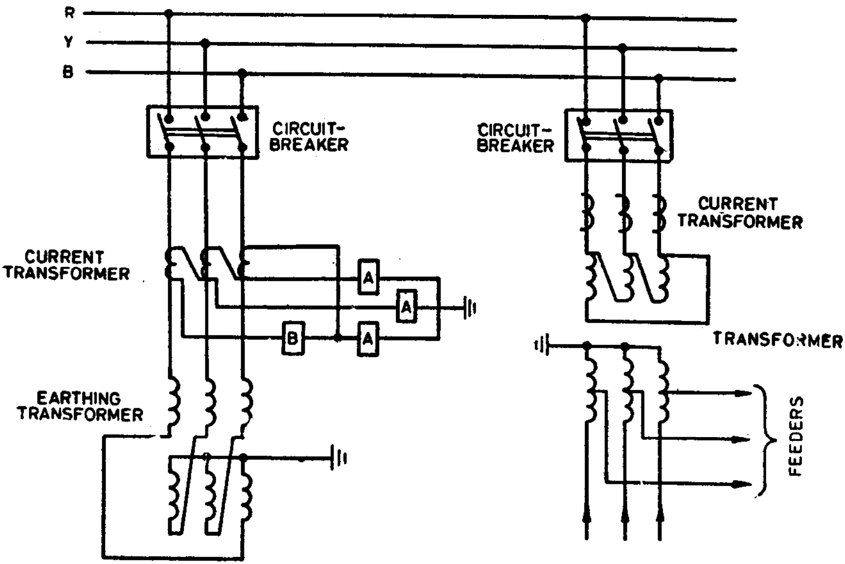


FIG. 25 EARTH-FAULT PROTECTION OF TRANSFORMER IN PARALLEL

7.4.5 *Protection of Earthing Transformers*

7.4.5.1 Earthing transformers provide an earthing point for the power system. They are connected in star-delta or in zig-zag formation. The neutral of either type may be earthed solidly, or through a resistance.

7.4.5.2 Whenever a fault occurs in an earthing transformer it contributes zero sequence current only and the positive or negative sequence currents flow only towards it and not from it. Therefore, the faults in the earthing transformer may be easily protected by overcurrent relays fed by delta-connected current transformers. A triple-pole instantaneous overcurrent relay as shown in Fig. 26 provides protection for faults on the earthing transformer. The relays are set between 25 percent to 50 percent of the continuous rating of the earthing transformer. The primary current of the current transformers should be equal to the rating of the power transformer. It is usual to add a long time delay inverse-time overcurrent relay for back-up protection against external faults. This relay is connected within the delta connections of the current transformers as shown in Fig. 26. Only one single pole relay is considered adequate as during external fault conditions the currents will be circulated in the delta-connected current



A — Instantaneous overcurrent relay
B — External fault back-up overcurrent relay

FIG. 26 PROTECTION SCHEME FOR EARTHING TRANSFORMER

transformers. During external faults, zero sequence currents flow in the primaries of the current transformers and the back-up relay is energized. The time setting is chosen to co-ordinate with the thermal rating of the resistor (if used) or with the time settings of other earth-fault relays so as to isolate the transformer or bus-bar from the rest of the system on a persistent earth fault.

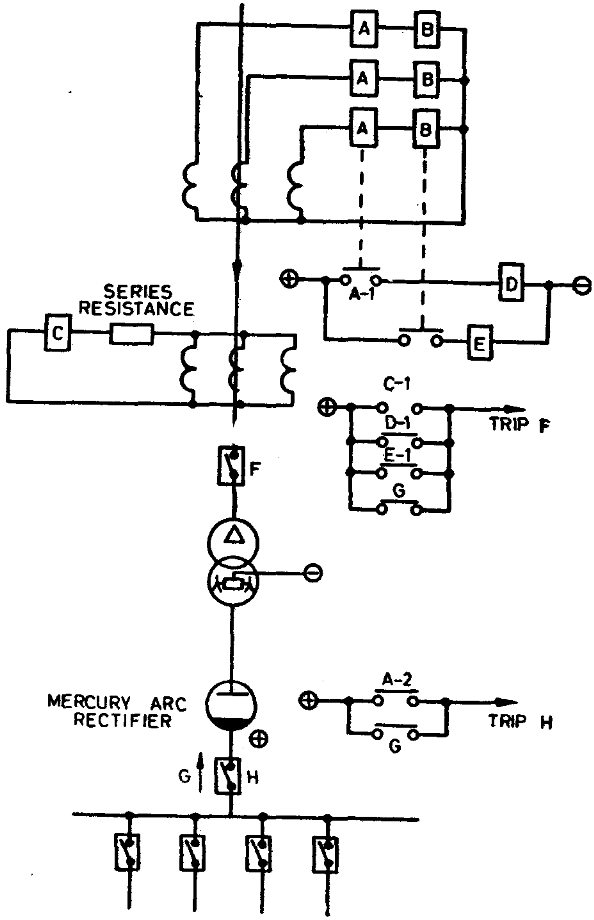
7.4.6 *Protection of Rectifier Transformer Units*

7.4.6.1 Overcurrent relays with very-inverse or extremely-inverse time characteristics may be used for the overload protection of rectifier transformers. Actual protection depends on the class and type of rectifiers, for example, mercury arc rectifiers or silicon rectifiers. Static relays with characteristics which closely match the overload characteristics of the rectifiers may be used.

The instantaneous overcurrent and instantaneous earth-fault relays are also used on the primary side of the rectifier transformer to protect against phase and earth faults on the primary winding. Instantaneous overcurrent relays will also protect against phase-to-phase faults on the secondary side, rectifier back-fires and heavy dc through faults.

7.4.6.2 For faults on the rectifier, like an arc back-fire, high speed anode circuit-breakers or high speed HRC fuses are used to clear them in a very short time, about 1 cycle or less. However, a time-lag overcurrent relay on the primary side of the transformer is normally provided as a back-up protection for this. This current setting is slightly above short-time rating of the rectifier and provides a time delay just high enough to ensure the necessary discrimination for the high-speed anode breakers or fuses to trip off. A time delay of 100 to 150 ms is generally provided and is sufficient to provide the necessary selectivity. For this, an induction type of relay with the extremely-inverse characteristic is generally used or an induction relay of the very-inverse type is provided to take care of overloads over the short-time rating and high-set relay (operating at about four times the continuous rating) with a time lag of about 80 ms is applied for the back-up protection against arc backs. In addition, an instantaneous overcurrent element is also provided to take care of internal faults in the transformer. This is set high enough to override the arc backs and dc-circuit faults. Where correct data is not available, a setting of about 8 to 10 times continuous rating of the transformer may be provided. An instantaneous earth leakage relay is generally added to provide the necessary protection on the primary winding if the earth-fault currents are not high enough to operate the high set relay.

7.4.6.3 In rectifiers where the anode fuse or anode circuit-breaker is not provided, the high set instantaneous overcurrent relay is set just above the magnetic in-rush value of the transformer and should protect the transformer and rectifier against arc backs also. If no data is given by the manufacturer these relays can be set to override the magnetization in-rush current.



A = Very-inverse time overcurrent relay
B = High-set instantaneous overcurrent relay
C = Restricted earth-fault relay
D = Time-delay relay
E = Slugged auxiliary relay
F = Main ac circuit-breaker
G = Direct acting reverse current trip
H = Main dc circuit-breaker

FIG. 27 A TYPICAL RECTIFIER UNIT PROTECTION FOR A CONSTANT VOLTAGE MERCURY ARC RECTIFIER

7.4.6.4 Figure 27 shows an example of the rectifier unit protection for a constant voltage mercury arc rectifier. Very-inverse time relays (range

50 to 200 percent) allow an overload duty of 200 percent for 15 seconds on the rectifier equipment and also detect summated overloads on the dc side. A time-delay relay (setting range 0·2 to 1 second) allows discrimination between dc and ac circuit-breakers. A high-set instantaneous overcurrent relay detects transformer and ac cable faults, rectifier backfires and heavy dc through faults on feeders and dc bus-bars. High-set relay operates a slugged auxiliary relay (about 5-cycle delay) which allows discrimination between the dc feeder circuit-breakers and the ac circuit-breaker on through faults. This auxiliary relay also prevents the high-set relay from tripping the ac circuit-breaker on transformer magnetizing in-rush current. The high-set relay is normally set at four times the full-load current. Restricted earth-fault relay is provided on the primary side of rectifier transformers and protects the delta winding against earth faults. Direct acting reverse current trip may be provided on the main dc breaker to detect back-fires fed from the dc system.

7.4.6.5 As mentioned above, the rectifier unit protection depends on the class and the type of rectifiers used. With silicon rectifiers, the overcurrent relay settings should be carefully selected so that correct discrimination is achieved between the diode fuses and the relays for external faults and for faults on the diodes.

8. DIRECTIONAL RELAYS

8.1 General

8.1.1 The overcurrent relays discussed so far are suitable for circuits in which the fault current can flow in one direction only or if the magnitude of the fault current in one direction happens to be several times that of the fault current in the other direction. To obtain selectivity when fault current of about the same magnitude may flow in either direction, the directional feature is essential.

8.1.2 Directional relays are commonly used for selective tripping of the breakers at the receiving end of parallel lines or in a ring main system. They are also used to trip the circuit-breaker of an earthed neutral generator or transformer, if more than one source may supply earth-fault current.

8.1.3 Directional relays are used:

a) with instantaneous overcurrent relays, if the maximum back-feed current is more than 80 percent of the maximum far-end current;
b) with time-delay overcurrent relays, if the maximum back-feed current is more than 25 percent of the minimum far-end current; and
c) if the load current is in the non-trip direction and the pick-up setting of the overcurrent relay of less than about twice the full load current is desired.

8.1.3.1 The above three points are explained in Fig. 28.

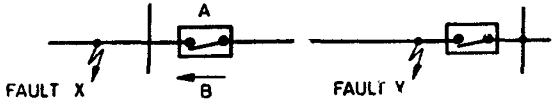


FIG. 28 AN EXAMPLE OF USE OF DIRECTIONAL RELAY

8.2 Directional Relays for Short-Circuit Protection — Two types of relays (*see* **8.2.1** and **8.2.2**) may be used for protection against short-circuits. The former is more common and single-phase relays of this type protect against phase faults as well as earth faults. However, 3-phase directional overcurrent relays are also sometimes used for uncommon conditions under which the single-phase relays may maloperate. The product type directional relays are often used for protection against earth faults.

8.2.1 *Directional Overcurrent Relays*

8.2.1.1 The directional overcurrent type of relay is a combination of overcurrent element and a directional element mounted in the same case.

8.2.1.2 The overcurrent element is similar in all respects to the non-directional overcurrent relays, already described, except that its operation is controlled by the contacts of the directional element.

8.2.1.3 The directional element is usually very sensitive and responds to about 1 percent of the full-load current at rated voltage at maximum torque angle. One method of providing the directional feature is achieved by allowing the overcurrent relay to operate only if the fault current is in the trip direction. In this case the overcurrent element does not even begin to operate until the contacts of the directional element are closed. This type of relay is referred to as *directionally-controlled* type.

8.2.1.4 Another method used for controlling the operation of the overcurrent element is to connect the contacts of the directional and overcurrent element in series in the circuit-breaker trip circuit and this type is referred to as *directionally-supervised* type. This is very rarely used because incorrect tripping under certain circumstances may take place, for example, when a very large current flows in the non-tripping direction, it may operate the overcurrent element if just at that time suddenly the direction of the current flow reverses, the directional unit may close before the overcurrent element has reset itself.

8.2.1.5 In Fig. 29 a schematic arrangement of the directionally-controlled overcurrent relay of an induction type is shown.

8.2.2 *Product Type Directional Relays* — Product type directional relays are virtually sophisticated wattmeters only and are used for very sensitive earth-fault protection. Inverse-time characteristics may be achieved with

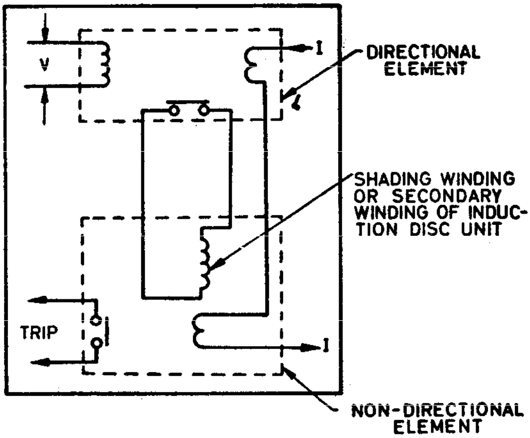


FIG. 29 SCHEMATIC CONNECTIONS OF DIRECTIONAL OVERCURRENT RELAY

this type of relay but since the characteristics are affected by the current, voltage, and the phase angle between them, the setting and co-ordination of these relays becomes very complex. Therefore, the advantages of sensitivity and selectivity possessed by the product type relays are of minor importance in most of the applications.

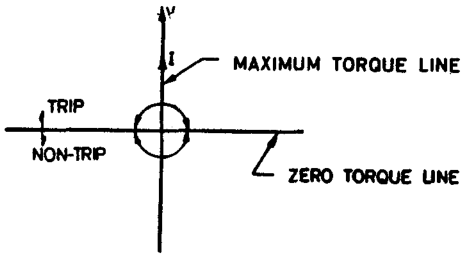
8.2.2.1 The directionally-controlled overcurrent relay is very easy to set and co-ordinate because like the non-directional overcurrent relay the time-current characteristics are based on the magnitude of the fault current only. This relay imposes higher burden than the product type relay, on the current transformers. Therefore, the product type relay has been preferred, though very rarely now, for protection against earth fault^

8.3 The Operating Characteristics

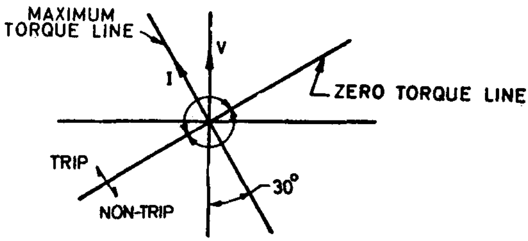
8.3.1 The directional relays are actuated by two independent quantities, current and voltage, or two currents or two voltages. The operating torque is a function of the two actuating quantities and the phase angle between them. Consequently, one of the actuating quantities should remain fixed when the other quantity suffers wide changes in its phase angle under different kinds of faults. The actuating quantity which is used as a reference is known as the 'polarizing quantity' and its choice is rather important for the proper application of directional relays. This is dealt with in detail in **8.4**.

8.3.2 The operating characteristics of typical directional relays, both wattmeter type and induction cylinder type, are shown in Fig. 30. It is obvious that the relay develops maximum torque for a specific phase angle

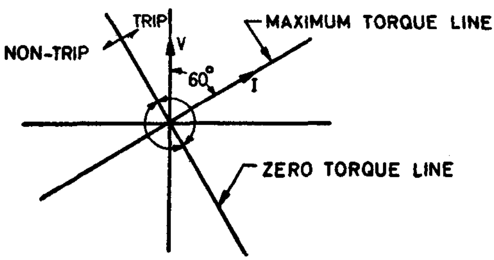
relationship between the actuating quantities. The zone of operation extends to 90° on either side of the maximum torque angle line. It may, however, be added that the zero torque line is a zone of no operation and not a thin line through the origin as may be imagined from the typical characteristics shown. The angle of the maximum torque may be varied by incorporating phase shifting networks.



30A Wattmeter Type Directional Relay



30B Cylinder Type Directional Relay for Phase Faults



30C Cylinder Type Directional Relay for Earth Faults

FIG. 30 OPERATING CHARACTERISTICS OF DIRECTIONAL RELAYS

8.3.3 However, the characteristics of the relay alone is not enough and knowledge of the phase angle relationship between the energizing quantities should be analysed to connect the directional elements suitably to protect

against different kinds of faults, that is, the connections of the directional elements should be properly chosen. This is dealt with in **8.4**.

8.3.4 Although it is possible to have directional relays with any maximum torque angle, the most common of them have the following values:

a) *For phase faults* — Current leads the voltage by (1) 30° or (2) 45°, and

b) *For earth faults* — Current lags the voltage by (1) 60° or (2) 45°.

NOTE — Voltage is regarded as the polarizing quantity.

8.4 Connections for Directional Relays (Polarizing Quantity for Directional Relays)

8.4.1 The choice of a particular directional relay depends on the connections of the relay (polarizing quantity) and location of the relay in the power system. As is well known, under different types of short-circuits, the phase angle relationship between the energizing quantities will vary considerably, for example, the current lags behind its unity power factor by 60° to 70° for a phase fault on long-transmission lines, and between 30 to 60° for the same fault on distribution and sub-transmission lines. The phase angle relationship for a phase-to-earth fault is not the same as above and is also modified by the fault arc resistance. Thus maximum torque angle of the directional relay should match the behaviour of the system currents and voltage under different types of faults, that is, for most of the faults, the fault current should be in phase with the maximum torque line of the directional relay.

8.4.2 *Connections for Phase-Fault Relays* — Three types of connections, that is, 90°, 60°, and 30° (which are also referred to as quadrature median and adjacent respectively) are used. These indicate the phase angle relationship between the energizing quantities under normal system operation at unity power factor. For each of these connections, the currents and voltages to be used are given in Table 1.

TABLE 1 VOLTAGES AND CURRENTS FOR DIFFERENT CONNECTIONS OF PHASE-FAULT DIRECTIONAL RELAYS

CONNECTION DIAGRAM	RELAY MAXIMUM TORQUE ANGLE	RELAY *R*		RELAY *Y*		RELAY *B*		MAXIMUM TORQUE WHEN CURRENT LAGS UNITY POWER FACTOR BY (DEGREES)
		V	*I*	*V*	*I*	*V*	*I*	
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
90°	30°	V_{YB}	I_R	V_{BR}	I_Y	V_{RY}	I_B	60°
90°	45°	V_{YB}	I_R	V_{BR}	I_Y	V_{RY}	I_B	45°
60°	0°	V_{RB}	I_R-I_Y	V_{YR}	I_Y-I_B	V_{BY}	I_B-I_R	60°
60° *Y*	0°	$-V_B$	I_R	$-V_R$	I_Y	$-V_Y$	I_B	60°
30°	0°	V_{RB}	I_R	V_{YR}	I_Y	V_{BY}	I_B	30°

The 90° connection is employed for most applications with a directional relay which has a maximum torque angle of 30° or 45° (current leads voltage).

8.4.3 *Connections for Earth-Fault Relays* — Directional earth-fault relays with a maximum torque angle of 45° (current lags voltage) is very commonly used. The voltage coil of the relay is connected to the tertiary winding of a 3-phase 5-limb voltage transformer. The tertiary winding is connected in broken-delta and the voltage is the sum of the 3-phase-to-neutral voltages. Three single-phase voltage transformers may also be used. The connections of the voltage transformer are shown in Fig. 31.

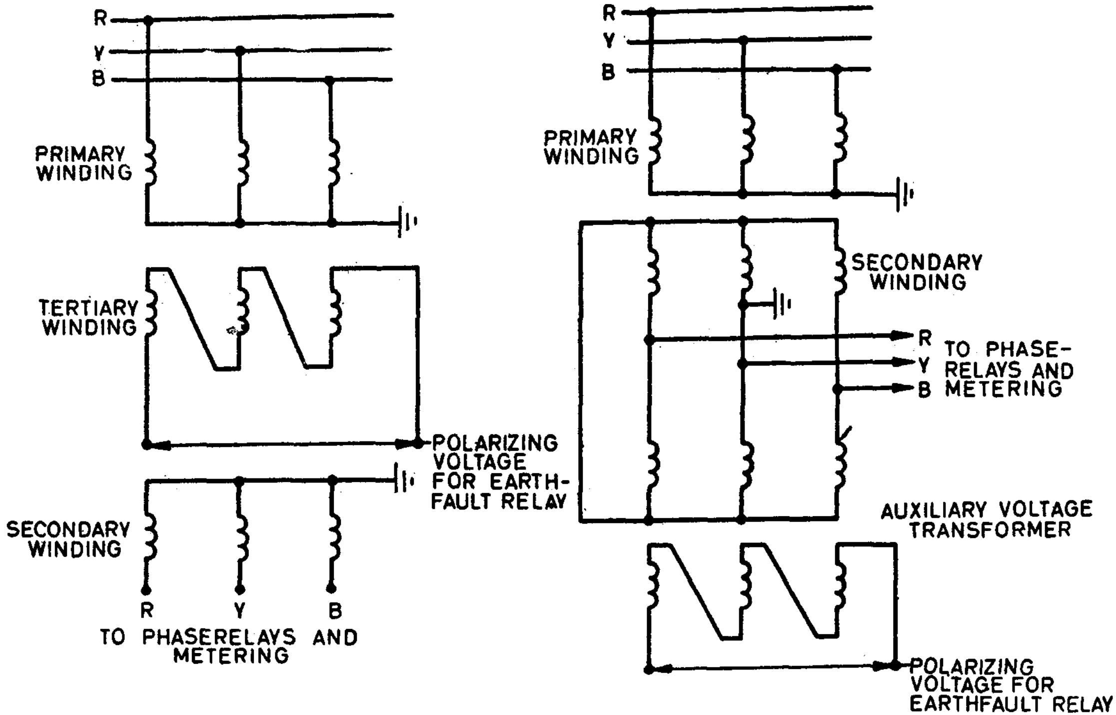
Although voltage polarization meets practically all the applications of directional earth-fault protection, relays having current polarization are recommended where the transformer banks are solidly earthed and the line impedance is high compared to the impedance of the transformer bank. As it may result in a residual voltage of low magnitude for the remote end faults, dual polarized directional units (that is, having voltage as well as current polarization coils) are desirable at such locations. However, on modern voltage polarized relays which will work down to 1 percent or less, it is not necessary to go to the extent of using the dual polarized directional relay as a residual voltage of less than 1 percent of normal is not experienced in actual practice.

8.5 Use of Directional Relays on the Secondary Side of the Transformer — Directional relays may also be used on the secondary side for the protection of parallel transformers as shown in Fig. 32. The secondary windings may be protected by three directional overcurrent relays against phase faults. 90° connection mentioned in **8.4.2** with a relay having a 45° maximum torque angle is best suited for this application. If proper settings and current transformer ratios are selected, the directional overcurrent relays can also provide protection for phase faults on the delta (primary) side of the transformers. For earth-fault protection it is common to provide restricted earth-fault protection on the secondary side.

8.6 Setting and Co-ordination of Directional Overcurrent Relays

8.6.1 The principles of setting and co-ordinating the directional phase-fault and earth-fault relays are the same as described for non-directional overcurrent relays. Figure 33 shows a typical loop system where directional relays are applied. Starting at station *A* in the clockwise direction, co-ordination between the relays should be as follows:

a) 1 with 3,
b) 3 with 5 and 6,
c) 6 with 8,
d) 8 with 10 and 11,
e) 5 with 11, and
f) 11 with 9 and 1.



31A Voltage Transformer with Tertiary Winding

31B Voltage Transformer with an Auxiliary Voltage Transformer

FIG. 31 METHODS OF OBTAINING POLARIZING VOLTAGE FOR DIRECTIONAL RELAYS

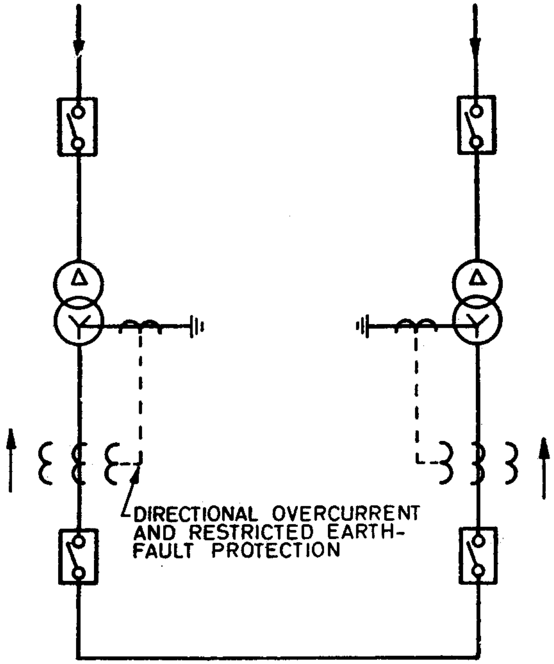


FIG. 32 PROTECTION OF PARALLEL TRANSFORMERS

8.6.2 In the anti-clockwise direction, starting from station B, the co-ordination between the relays should be as follows:

a) 2 with 10 and 9,
b) 9 with 7,
c) 7 with 5 and 4,
d) 4 with 2,
e) 10 with 12, and
f) 10 with 4 and 6.

8.6.3 The co-ordination in such a system is a matter of trial and error, especially for earth-fault relays. Wherever possible, instantaneous over-current phase-fault relays should be applied, thus reducing the overall tripping time and achieving better selectivity.

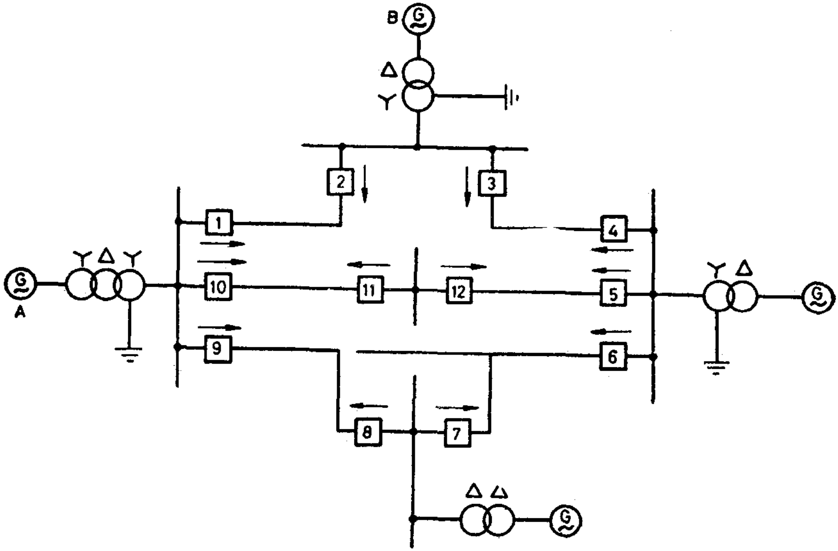


FIG. 33 TYPICAL INTERCONNECTED POWER SYSTEM FOR THE APPLICATION OF DIRECTIONAL OVERCURRENT RELAYS

8.7 Polyphase Directional Relays

8.7.1 In rare applications these relays may be used in place of single-phase directional elements for polarizing the overcurrent relays against inter-phase faults.

8.7.2 Polyphase directional relays are often used to polarize the earth-fault relays also. However, these relays have lowest sensitivity for single phase-to-earth faults, because torque due to the two healthy phases opposes that due to the faulty phase and are therefore used only when the minimum earth-fault current is more than about three times the maximum load current. This requirement is easily met on solidly-earthed systems.

8.7.3 These relays are sometimes used for selecting the faulty feeder in transverse differential or parallel feeder protection.

9. SUMMARY OF COMMON APPLICATIONS

9.1 Summary of common application of different types of time relays is given in Table 2.

TABLE 2 COMMON APPLICATION OF DIFFERENT TYPES OF TIME RELAYS

Definite Time Relays	Instantaneous Relays	Inverse and IDMTL Relays	Very-Inverse Relays	Extremely-Inverse Relays	Special Inverse Relays
		Characteristics			
Definite time	Operating time up to 240 ms	Refer **9.1.1.1** of IS : 3231-1965*	$IT=K$	$I^2T=K$	$I^{2.5}T=K$
		Applications			
1. Radial or loop circuits having few sections in series (*see* **4.2**) 2. On systems with variation of fault current due to wide variations in source impedance (*see* **4.2**) 3. Back-up for differential and distance protection (*see* **4.2**)	1. Transformer feeders (*see* **4.3**) 2. Places where there is substantial difference in short-circuit currents between two relay locations (*see* **4.3**) 3. Near the source of power, used along with definite or inverse relays on systems where source impedance does not vary widely (*see* **4.3**)	1. Radial or loop circuits having large number of sections in series with difference in fault current between relay locations (*see* **4.4.1**) 2. On systems where system fault current at a particular point does not vary very widely due to the changes in source impedance (*see* **4.4.1**) 3. Back-up for differential and distance protection (*see* **4.4.1**)	1. Feeders supplied from large generating systems where the magnitude of short-circuit current is practically constant (*see* **4.4.2**) 2. Long sub-transmission lines where there is a substantial reduction in fault current as the distance from the power source increases (*see* **4.4.2**) 3. Loop systems where it is necessary to have approximately the same interval between operating times for faults at the near end and far end of the protected section (*see* **4.4.2**) 4. Where fast operation is required over a restricted current range (*see* **4.4.2**)	1. Distribution network (*see* **4.4.3**) 2. System where discrimination with fuses is required (*see* **4.4.3**) 3. Against overheating of apparatus, such as earthing transformer or power transformer cables (*see* **4.4.3**) 4. Places where there are large in-rush currents after an outage (*see* **4.4.3**)	1. For specific applications (for example, mercury arc rectifier) (*see* **4.4.4**)

*Specification for electrical relays for power system protection.

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